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FACULTY OF MINING AND METALLURGY

A DISSERTATION SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS FOR A MASTER OF TECHNOLOGY IN EXTRACTION METALLURGY

A REVIEW OF VENTILATION AND COOLING SYSTEMS APPLIED IN DEEP AND ULTRA-DEEP MINES TO IMPROVE SAFETY AND PRODUCTIVITY: A CASE STUDY OF SOUTH AFRICAN GOLD MINES

by

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DECLARATION

I Tendai Mapeta, declare that this dissertation is my effort with the guidance of my supervisor. Otherwise, other sources from where I took materials are fully quoted and referenced. I am very proud to submit this dissertation entitled, "A review of ventilation and cooling systems applied in deep and ultra-deep mines to improve safety and productivity: a case study of South African gold mines." for the Degree of Master of Technology in Extraction Metallurgy (MTECH) to the University of Johannesburg, Republic of South Africa.

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ABSTRACT

The heat load and cooling requirements in deep mines will be significantly higher than in most shallow existing mines. Mines implement ventilation and cooling systems and controls to provide a conducive working environment. In the South African mining industry, the crucial focus has often been on heat stress management because as mines progress deeper, there is an equal inevitable increase in virgin rock temperatures. Research indicates that high temperatures reduce the productivity of stope workers, as well as influence their health and safety. An ascent in the body temperature gives way to known heat illnesses such as heat stroke. Research confirms that there are multiple means to minimise the heat load and mitigate the heat being produced. Such controls include engineering and administrative controls at the source. This study aims to improve ventilation practices and procedures for the established narrow tabular deep level gold mines.

This research study is based on gold mine case studies where mixed research methods were employed such as qualitative and quantitative approaches. The respondents of this study for the quantitative questionnaire were ventilation specialists.

The quantitative questionnaire was used to interview the ventilation specialists to obtain their opinion on ventilation and cooling methods currently being implemented, as well as their opinion on future ventilation and cooling requirements for deep and ultra-deep gold mining in South Africa. Structured interviews and ventilation reports were used to provide the opportunity to relate different ventilation specialists views to specific research objectives such as their opinions on the use of in-stope atomisers for in-stope cooling concerning its effectiveness against these high temperatures, cooling garments as a microclimate method of cooling and its possibility of adoption into the South African mining industry, functions and data of the cooling car as a cooling method, and elaborating on the challenges connected to utilising in-stope coolers.

Qualitative data collection methods include key informant interviews and participation observations. Secondary data of companies' ventilation reports were obtained from the mines under investigation in this study. The research gained in the field, i.e. case studies, was also used to compare to what was gathered in the literature review, as well as comparing the case studies results with other results obtained from data provided by ventilation specialists.

The results of the research concur with previous findings that high temperatures reduce the productivity of stope workers, as well as have a negative influence on their health and safety. An ascent in the body temperature gives way to heat stroke. There are multiple means to minimise the heat load and remove this

heat being produced, such as the use of cooling garments and spot coolers; by applying such controls including engineering and administrative controls at the source. Cooling cars and in-stope (spot) cooling systems and controls can be used to alleviate the detrimental effects of thermal stress, such as reduced performance and lower productivity, and reduce the safety and health risk of stope workers where ventilation and refrigeration do not function adequately.

This study also reveals that cooling rooms, which are underground small-sized rooms located close to the working areas or within the stope are uncommon in the South African gold mines. The challenge with cooling rooms is related to their construction and maintenance. In these case studies, mine management was of the opinion that any cooling method that relied on the workers to self-manage often did not end with positive results. Management suggested that it was often not easy to get South African workers to cooperate and comply with the implementation of any new method. This is because workers often comply only with what increases their incomes and bonuses and the rest is considered a hinderance.

In certain circumstances, ventilation controls might not be effective, and body-cooling garments may be used to regulate the worker's microclimate by reducing their core body temperature. Spot coolers can also be effective if the correct engineering practices are followed, especially consistent maintenance.

A shortfall in the South African heat stress management system is that it is based on data that were recorded many years prior to the introduction of underground female workers, thus, the current guidelines do not consider the heat tolerance levels for women in mining. It is recommended that research further investigates and revise the current heat stress management standards and guidelines.

The main conclusion, drawn from this research is that there are challenges that come with any selected cooling strategy, for example, cost, impact cycle times, and productivity. This research showed the need for each mine to adapt to the cooling or strategy that best suits its operation. Most ventilation systems have been used together with bulk air coolers and cooling cars located in the crosscuts in an attempt to provide sufficient cooling to maintain in-stope temperatures below the legal limits. However, the research, as well as other ventilation specialists, query if ventilation and cooling standards are outdated and that they should be reviewed and potentially revised.

The South African mining industry can benefit from the outcomes of this work, especially through the study of the current temperatures being experienced underground, and the ventilation and cooling systems being adopted. The research has the potential to provide a significant step towards appropriate ventilation and cooling strategies and methods required to reduce the temperatures in deep level gold mines. In particular, by reviewing ventilation and cooling standards and practices currently in place, especially in light of the industry’s target of having a zero-harm mining environment.

DEDICATION

This study is wholeheartedly dedicated to My Father, Arnold Mapeta for supporting and believing in me. Teaching me that the sky is the limit.

To my Mother, Catherine Mukau Mapeta, a strong and gentle soul. Thank you for all your unceasing prayers that have sustained me to come this far.

My sisters for always being positive and unbreakable, never throwing in the towel. Standing to win. Thank you for the inspiration and love and sincere friendship.

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LIST OF ABBREVIATIONS

- ACG – Air-Cooled Garment
- ATP – At this point
- BAC – Bulk Air Cooler
- BBE – Bluhm Burton Engineering
- CCT – Condenser Cooling Tower
- CET – Corrected Effective Temperature
- COP – Mandatory Code of Practice
- CSA – Canadian Standards Association
- CSIR – The Council for Scientific and Industrial Research
- DB – Dry Bulb
- dD – Change in Distance
- DM – Deep Mine
- DMR – Department of Minerals Resources
- DWB – Dry Wet Bulb Temperature
- $D\theta$ – Change in Temperature
- EHSI – Emergency Heat Stress Index
- EIA – Environmental Impact Assessment
- ERPM – Enterprise Random Password Manager
- ET – Effective Temperature
- FGDs – Focused on Group Discussions
- IMF – Ice Mass Fraction
- LCGs – Liquid-Cooled Garments
- LoCM – Longevity of Current Mines
- MHSA – Mines Health & Safety Act
- MOSH – Mining Industry Occupational Safety and Health
- NASA – National Aeronautics and Space Administration
- NCG – Non Condensable Gases
- NIOSH – The National Institute for Occupational Safety and Health
- OHS – Occupational Health and Safety
- PCG – Phase Change Garment

- PPE – Personal Protective Equipment
- PVC – Poly Vinyl Chloride
- SAMERDI – The South African Mining Extraction Research, Development, and Innovation
- SCP – Specific Cooling Power
- SIMRAC – Safety in Mines Research Advisory Committee
- TWB – Wet Bulb Temperature
- VIM – Vacuum Ice Machine
- VOD – Ventilation on Demand
- VRT – Virgin Rock Temperatures
- W – Watts
- WB – Wet Bulb
- WHO – World Health Organisation

LIST OF UNITS

- " – Inch
- % – Percentage
- °C – Degrees Celsius
- cm – Centimetres
- kg – Kilogram
- kg/s – Air handled
- kg/m³ – Air Density
- kJ – Kilojoules
- kJ/kg°C – Specific heat of water
- kJ/kg – Latent Heat of ice
- km – Kilometre
- J/kg°C – Specific heat
- kPa – Pressure
- kW – Kilowatts
- lb. – Pound
- lb. – Pound
- l/s – Water Flow
- m – Metres
- m2 – Area
- m\s – Velocity
- m²/s – Thermal diffusivity
- m/°C – Geothermal step
- m3/ sec – Volumetric flow rate
- m3/hour – Rate of delivery
- m – Metres
- mbs – Metres below Surface
- mm – Millimetres
- MW – Mega Watts
- NB – Nominal Bore
- USD – United States of America Dollars

- W – Watts
- W/m2 – Rate of Work
- W/m°C – Thermal conductivity
- ZAR – South African Rand (1USD = R16.69 (7/18/2020))

CHAPTER 1: INTRODUCTION

The South African gold mining sector has proved to have one of the most challenging working conditions in the world. The ventilating air that circulates through a mine is heated by different sources resulting in working places in deep and ultra-deep mines being very hot. One of the fundamental purposes of mine ventilation is to keep working places as cool as possible (Hardcastle & Butler, 2008). That is why the environmental conditions and effective temperature (ET) in underground stopes have been managed and maintained within an acceptable range to avoid the exponential rise in occupational hazards and operating costs, which is achieved by compliance with legal restrictions. Massanés *et al*. (2015) came to the conclusion that in general, performance and productivity decrease as the ET or corrected effective temperature (CET) exceeds 30°C.

Underground hard rock mines, especially gold mines, are faced with challenges that lead to a decrease in the productivity of employees. A portion of these difficulties was identified through the Longevity of Current Mines (LoCM) Programme of the South African Mining Extraction Research, Development, and Innovation (SAMERDI) strategy. The LoCM Programme identified the lack of adequate ventilation, cooling, and the lack of realtime monitoring environment conditions as areas requiring further research and development.

Cooling of the underground environment is carried out by designing the ventilating systems of a mine so that sufficient ventilating air flows through each and every excavation to absorb and carry the heat out of the mine. It is important to understand that at extreme depth, large volumes of air alone are not adequate to achieve this. The in-take air must be cooled in order for it to sufficiently ventilate the underground environment (McPherson, 2012).

By applying such controls including engineering and administrative controls at the source, such as cooling cars and ventilation controls, ventilation and cooling are used to alleviate the effects of high temperatures and mitigate against thermal stress and reduced work performance.

The motivation of this research project arose from the fact that the South African gold mining industry can benefit from the outcomes of this work, especially through the study of the current temperatures being experienced underground and the method used to provide a conformant work environment. The research has the potential to improve ventilation and cooling methods used to reduce the temperatures in the deep gold mines of South Africa and create a stoping environment that promotes a zero-harm environment.

Previous research indicates that high temperatures reduce the productivity of stope workers, as well as negatively influence their health and safety. An ascent in the body temperature gives way to known heat illnesses such as heatstroke. Research confirms that there are multiple means to minimise the heat load and remove this heat being produced. By applying appropriate ventilation and cooling strategies and controls, including engineering and administrative controls at the source, conformant stope environments can be realized with the goal to achieve less than 28°C reject temperatures. Bulk air cooling and the use of cooling cars can alleviate the effects of high virgin rock temperatures and mitigate against thermal stress and lower productivity.

1.1 Background

Specialists often refer to ventilation as the lifeblood of a mine, the intake airways being arteries that carry oxygen to the working areas, and the return airways as veins that transport pollutants away to be expelled to the outside atmosphere. Without an effective ventilation system, no underground facility that requires personnel and machinery to enter it can operate safely (Marriott, 1993).

There is no machinery that can be introduced underground without a satisfactory supply of air. Mine ventilation engineers are caught up in a continuing cycle where their work permits rock to be broken at greater depths. This, on the other hand, creates more dust, gases, and heat, resulting in a greater need for better environmental control. History reveals ventilating strategies that include redirecting surface winds into the mouths of shafts, wooden centrifugal fans powered by men and horses, bellows for auxiliary ventilation, and air doors. Agricola (1912) was also very much aware of the dangers of blackdamp, the air that has suffered from a reduction in oxygen content, - “miners are sometimes killed by the pestilential air that they breathe,” and of the explosive power of "firedamp", a mixture of methane and air "likened to the fiery blast of a dragon's breath". From the 17th Century onwards, papers started to be presented to the Royal Society of the United Kingdom on the explosive and toxic nature of mine atmospheres (McPherson, 1993).

During Atkinson's productive years, the first power-driven ventilators started to show up. These differed from gigantic steam-driven piston and cylinder devices to basic centrifugal fans. In the years when the 19^{th} century rolled over it was observed that working conditions in mines were seen coming under legislative control. Mine manager's assessment papers focused vigorously on ventilation matters until well into the twentieth century (McPherson, 2012).

The 1920s saw additionally quickened research in several countries. Improved instrumentation permitted organised ventilation surveys to be carried out to quantify airflows and pressure drops for ventilation planning, even though there were no practical means of predicting airflows other than simple circuits at that time. Atkinson's theory was confirmed in practice. The main effective pivotal ideas were introduced in about 1930. In 1943, Professor F. Baden Hinsley produced another classical paper advancing understanding of the behaviour of airflow by using thermodynamic analyses. The work at Nottingham University prompted the first practical use of analog computers in 1952 to facilitate ventilation planning. This technique was utilised widely and effectively for over 10 years when the development of ventilation network analysis programmes for digital computers in the early 1960s rendered the analog devices obsolete. At first, the network programmes were written for, and required the power of mainframe computers. These were employed throughout the seventies. However, the 1980s saw a shift to desktop computers, and corresponding programmes were developed. This is presently the dominant method utilised for ventilation planning (McPherson, 2012).

1.2 Research Problem

South Africa's gold sector is a world leader in deep-level gold mining. Deep-level underground mining, however, brings with it risks and hazards that require constant commitment and adherence to safety and health standards and procedures. High temperatures and high humidity levels in some underground mines create stressful working conditions and can decrease productivity (Department of Mineral Resources, 2015). Cooling is therefore essential to ensure the environment meets the mental and physical needs of the workers, allowing for a safe and productive working environment.

This study aimed to improve ventilation practices and procedures for the established narrow tabular deep level gold mines, already constrained by their infrastructure, to prolong their sustainability, thereby maintain current jobs. This is achieved by improved ventilation and cooling, which should as a result improve the productivity and safety of the workers.

1.3 Aim of the Study

Cooling system configurations can vary, however, in general, normal ventilation, followed by surface and underground bulk air cooling systems and eventually ice systems is the order in which cooling systems should be implemented.

The aim of this study was to provide an evaluation of proposed ventilation and cooling methods and their impact, allowing for a complete understanding of the current temperatures being experienced in underground operations and the methods of mitigation being currently adapted.

1.4 Objectives of the Research

The broad aim of this research was to study current environmental conditions in mines, to analyse the cooling methods adapted in these operating mines, to reduce temperatures, and promote increased productivity and safety in deep level gold mines.

In most instances, chilled water has been used, but now South African gold-mining has reached the point where ice is a better option for any new deep mine (Nunes & McPherson, 2002). The study compared ice and water as a cooling medium used in the mines. Further, the functions, advantages, and processes of an ice plant were also studied. Also, a review of a proposed extension of a deep level gold mine was carried out to provide an example of the role ventilation and cooling plays in current mine designs.

It is generally recognised that providing acceptable temperatures at reasonable costs within the underground workings is one of the main practical limitations to the depth of mining. Due to heat pick-up within haulages and stopes, ventilation must be cooled to approximately 28°C (wb) before entering the working area. The air is then either removed to the return airway or in some instances it might be required to remove air from the working area, re-cool, and re-treat it so that it may be reintroduced back into stopes. For some mining layouts, it may be practical to provide cooling within the stope environment. The above statement was strengthened with the following caveat: "this is enabled through partnerships in research and development, skills and competitive local manufacturing capability that will focus on the current and future mining operations through next-generation mining systems. To achieve this, a just transition must be at the core" (Harmony Gold, 2009).

The objectives of this study are as follows:

Objective 1: **Conduct an extensive literature research on underground mine ventilation and cooling systems.**

Objective 1 allowed for the understanding of past work, its analysis, and suggestions. Revealing the gaps that come with unimplemented ideas and methods. This objective also permitted the evaluation of proposed methods and their impact.

Objective 2: Evaluate the current underground in-stope temperatures and the cooling methods adapted to mitigate high stope temperatures using ventilation study reports for Mine A, B, C, and D.

Objective 2 took this research one step further by studying the cooling methods adapted in deep level gold mines. The choice of the method is frequently controlled by the capital and operating costs amongst other challenges, although these factors were not within the scope of this study. An important contribution of this research work was the study and analysis of cooling garments as a method of micro-climate cooling, cooling of the area directly surrounding the mine worker, backfilling as a method to improve air flow, the use of cooling cars and spot coolers in the cross-cut, the importance of ventilation brattices to direct cooled air, and the effectiveness of atomisers as a cooling method in the stope.

Objective 3: Formulate recommendations and opinions of the standard environmental conditions acceptable for efficient working conditions as well as to protect the health and safety of underground workers and improve productivity.

Objective 3 analysed the recommendations and opinions of the standard environmental conditions acceptable for workers to protect their health and safety. Awarding the opportunity, therefore, to gain a variety of professional views to contribute to the proper conclusion of the topic by using interviews, discussions, and mine ventilation reports. A visit to the mine catered to the comparison of theory with practice allowing for a complete understanding of the current temperatures being experienced underground and the methods of mitigation being currently adapted.

1.5 Research Questions

In order to meet the objectives of this research, the following research questions were answered:

1. ***Cooling garments are at times considered to be impractical for various reasons such as cost, weight, mobility thus, under what conditions can the use of cooling garments be ideal for the worker?***

Cooling garments are not common in the South African mining industry and are thought to be expensive. However, an important contribution of this research work was the study and analysis of cooling garments as a method of micro-climate cooling.

2. ***In-stope cooling systems should be implemented to supplement a mine's existing ventilation and refrigeration system, what are the recommendations for in-stope spot coolers?***

Spot coolers are considered as secondary cooling systems. The research question evaluated their capacity, ways of improving effectiveness, design properties, and resistance for usage in the in-stope environment, amongst other factors.

3. ***Previous research and trials have been conducted on cooling cars in the cross-cut, what are recommendations to improve their cooling efficiency?***

As a part of engineering structures adapted by some mines, cooling cars supplement surface and bulk air-cooling systems in maintaining temperatures within legal limits. The research investigated the effectiveness of cooling cars in deep level gold mines.

4. ***What is the potential use of cooling rooms, rest periods, work cycles, and recommendations for drinking water in a hot working environment?***

Cooling rooms are refuge bay-sized rooms developed underground close to the working areas. These have not been used in South African mines. Canadian guidelines have found associations between the number of accidents to exhaustion and suggested that workers take breaks during a shift (Stinnette, 2013). Cooling rooms can be a good implementation in the mines as the worker takes a rest period. There are several well-documented physiological problems associated with loss of total body water (dehydration) in humans. Miners working in hot conditions can have very high sweat rates and suffer significant loss of body weight during their working shifts.

5. ***What is the current maximum temperature in light of a zero-harm environment and future requirement of the Mining Charter introducing near equality in the employment of women?***

Given the critical impact that performance and resultant productivity have on the achievement or failure of ultra-deep mining, worker performance criteria should form part of the fundamental basis for determining the thermal standards and exposure limits to be applied. Also, it could be essential for the current legal standards to be reviewed as the current limit of 32.5°C (wb) no longer reflects current safety requirements and may not be in sync with other international standards. This is because elevated temperatures remain a major hazard to underground personnel as mining progresses deeper and further from the shaft. And the temperature limits that have been proposed were based on data that was collected many years back.

Additionally, working underground is experienced differently by men and women, with women behaving differently from men in the stope environment due to their physiological difference. Regardless of these challenges, women in mining remain important for mines from the point of view of policy, specifically because it features so prominently in the Mining Charter.

1.6 Significance of the Study

In 2018, the mining industry contributed 7.3% to the South African economy through the gross domestic product (GDP) (Minerals Council South Africa, 2018). The mining industry contributes approximately R8 for every R100 gained by the national economy (Statistics South Africa, 2018).

Meanwhile, poor ventilation and cooling practices are known to have a negative impact on productivity and workers' health and safety as previously stated. This means that if gold mines are not producing enough, contribution to the national economy would be low, provided all other variables remain the same.

The methods of ventilation that were recommended in this study assisted mines to manage the hot working environments that workers are exposed to. This study also highlighted the relevance of the legal temperature limits that were established many years ago to the current underground environmental conditions.

1.7 Description of Ventilation and Cooling Concepts Applicable

Both qualitative and quantitative research methods were used in this research. Under quantitative methods, temperature statistics from the case studies (Mine A, B, C, and D) were put into consideration. Where data from the case studies were reviewed and organised, broken into manageable units and patterns studied. The interviews were structured according to themes to help align them to the objective of the research and ease the analysis of the qualitative data. These themes reflect the general aim and objectives in this research: cooling (methods), rest periods in cooling rooms, cooling garments, women in mining and, to conclude, acceptable environmental standards.

The qualitative relates to studying the extension project of Mine D and cooling methods used in Mines A, B, C, and D case studies. These qualitative methods included literature reviews of gold mines in South Africa i.e. studying past work and opinions from other researchers. Discussions with ventilation specialists added to the value of this qualitative method, to get an updated opinion of the current status of the underground environment.

1.8 Justification of the Study

Deep level underground mining brings with it risks and hazards that require constant commitment and adherence to safety and health standards and procedures. The high temperatures and high humidity levels in some underground mines create stressful working conditions that in turn decrease productivity (Department of Mineral Resources, 2015). Some South African gold mines are already operating at depths beyond 3500m such as Mponeng. The goal of this research was to study the current temperatures being experienced in deep-level underground gold mines, analysing the ventilation and cooling methods being used in these hot underground gold mines thereby establishing effective recommendations for cooling methods to be implemented in the industry.

While the underground mine environment is encountering these changes, mineworkers remain present in these declining climatic conditions (Greth, 2018). So, it is important that the workplace is made safe for workers. Numerous methods can be proposed yet how these systems are applied varied on a case by case basis for each mine dependent on a variety of factors.

1.9 Location and Proximity of the Research

Free State operations are located on the south-western corner of the Witwatersrand Basin, between the towns of Allanridge, Welkom, Theunissen, and Virginia. The basin, situated on the Kaapvaal Craton, has been filled by a 6 km thick succession of sedimentary rocks, which extends laterally for hundreds of kilometres.

Figure 1-1 shows the location of Harmony's Free State operations.

The Free State goldfield is divided into two sections, cut by the north-south striking De Bron Fault. This major structure has a vertical displacement of about 1500m in the region of Bambanani, as well as a lateral shift of 4 km. This lateral shift can allow a reconstruction of the orebodies of Unisel to the west of the De Bron Fault and Merriespruit to the east. Many other major faults (Stuirmanspan, Dagbreek, Arrarat, and Eureka) lie parallel to the De Bron Fault.

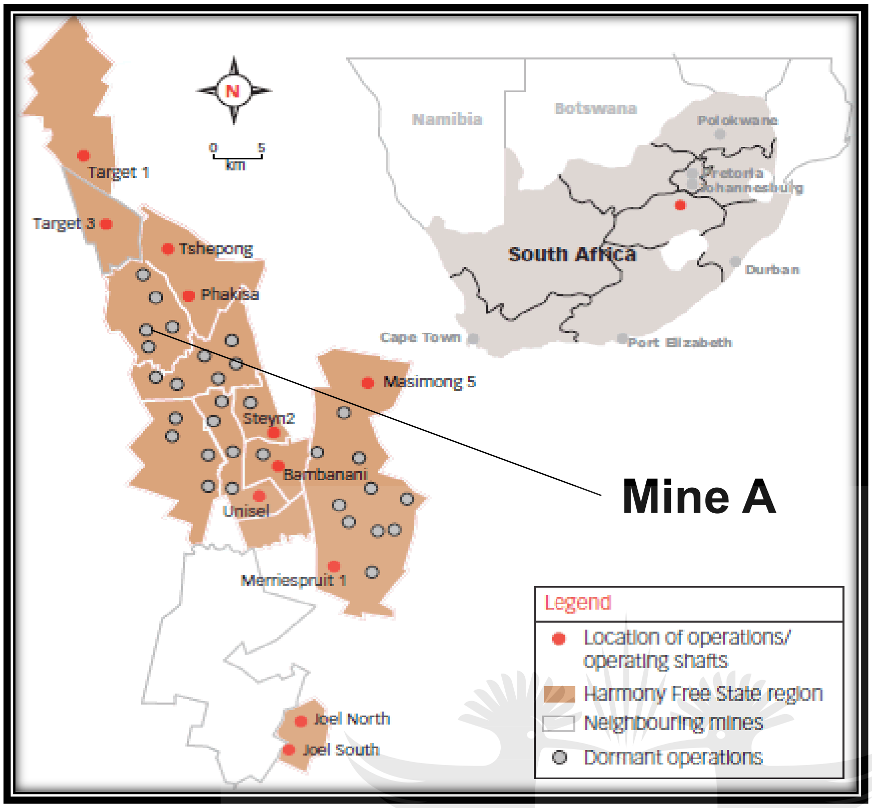

Figure 1-1: Location of Harmony's Free State Operations (Harmony Gold, 2009)

Mine A is located in the Free State as shown in (Figure 1-1). It mines the Basal Reef to a depth of approximately 2500m. It is serviced by hoisting a shaft located 5.5 km away and which is also used as a secondary escape route. Ore mined at Mine A is processed at a processing plant that is located some 20 km away. The mine is capable of employing about 1700 employees and 100 contractors giving an approximate total of 1800 people.

This mine (Figure 1-1) was selected as it is in the Free State mining district and represents typical conditions found in the Republic of South Africa (RSA) mining industry. It is not ultra-deep but due to the geothermal gradient of the Free State and the age of the mine, it operates in deep areas, as well as working areas that are far from the shaft.

Mining is concentrated on extracting pillars, as well as undisturbed blocks of ground. The underground workings are divided into ventilation districts. The shaft is ventilated with three surface fans (where only two operate at all times and one serves as a back-up fan) handling 770m³/s and a 21128kW bulk air cooler situated on surface cooling 450m³/s and also provide 120l/s of chilled service water to the underground workings.

The ventilation system is designed to remove heat which is a standard practice in mines. The ventilation and refrigeration system consists of ventilation circuits that ensure the stope face and development end conditions are maintained at a wet-bulb temperature of less than 32.5˚C (wb) and an air velocity that is greater than 0.4m/s (Department of Mineral Resources, 2002).

Mine B is located in the Free State (Figure 1-2) province, near Welkom, approximately 250 km from Johannesburg.

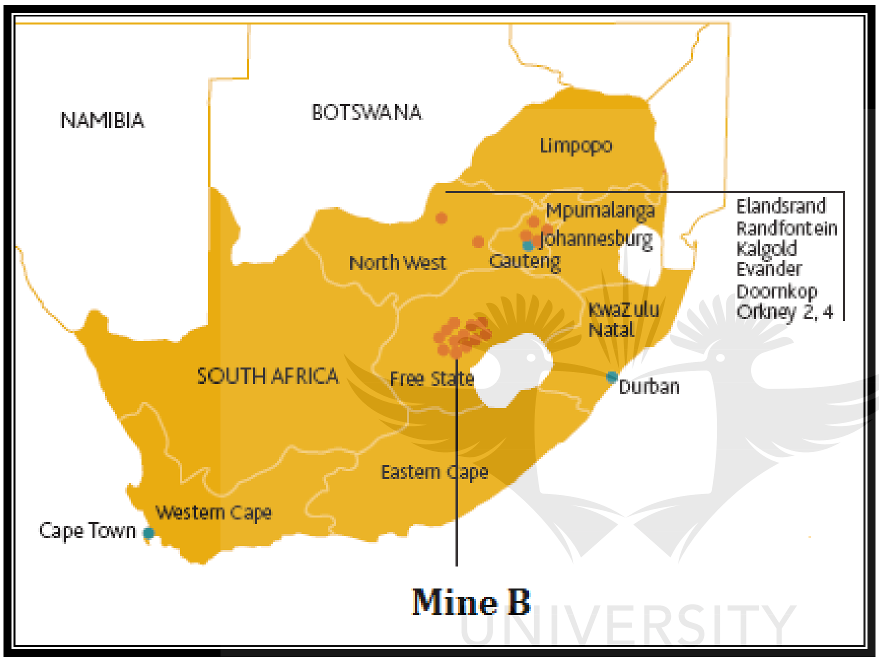

Figure 1-2: The map of Free State province (SA) depicting Mine B (Harmony Gold, 2007)

Mining at Mine B (Figure 1-2) is conducted at depths ranging from 1500m to 2300m. Mine B is a mature underground operation, using conventional mining methods. Rock is transported via a rail-conveyor system to the shaft, from where the rock is hoisted to the surface. The principal gold-bearing orebody is the Basal Reef and the B Reef.

Mine C is located in the Free State province (Figure 1-3), some 270 km southwest of Johannesburg. Mining operations comprise one primary underground shaft, to a depth of approximately 2300m below the surface where current mining takes place. Most of the ore extracted comes from mechanised mining long-hole stoping where reef widths allow this, and either cut-and-fill or long-hole stoping in narrow reef areas. Drift-and-fill mining is used in flat-lying reef areas.

Figure 1-3: The map of Free State province (SA) depicting Mine C (Harmony Gold, 2007)

The Mine C (Figure 1-3) shaft is used to transport personnel, material, and rock from surface to 203 level from where a single decline, equipped with a conveyor belt, connects to 255 level some 2050m below surface. The decline splits at 255 level into a conveyor decline and a vehicle decline, descending to the extent of development currently at 291 level, 2300m below surface.

Mine C's operational performance is focused on trackless development to ensure the timeous availability of massive stopes and to prevent excessive dilution from waste and backfill in the pillar areas, which could impact negatively the delivered grade.

Mine D (Figure 1-4), which is located on the Gauteng-North West Province border, comprises twin vertical and twin sub-vertical shaft systems. Mining is undertaken using conventional mining methods in a sequential grid layout. The deepening project, which is almost complete, involves the extension of the sub-vertical shafts to access the deeper parts of the Ventersdorp Contact Reef up to a depth of 3600m. Work on the project is currently focussed on accessing and opening up areas of the new mine and the development and construction of the necessary support infrastructure. Mine D employs 5 685 people.

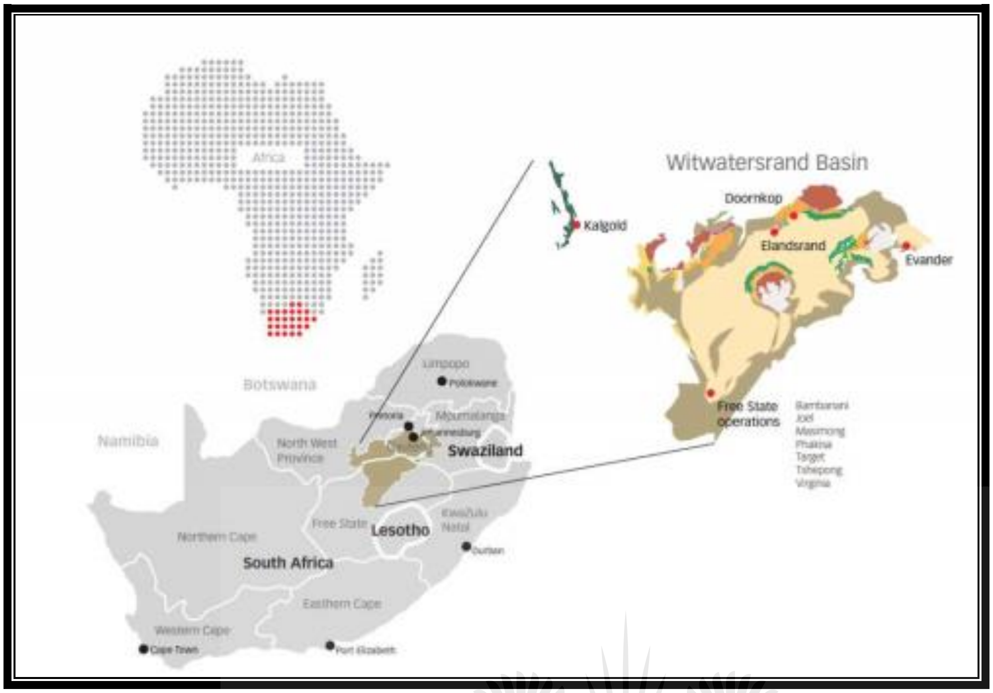

Figure 1-4: Locality map for Mine D after Harmony Gold Mining Company Limited, (Harmony Gold, 2009)

1.10 Applicability of the Research

The investigation of ventilation and cooling in deep-level underground gold mines of South Africa focusing on case studies of Mines A, B, C, and D located in the Free State, which was useful to current deep level gold mines that are also experiencing high temperatures as operating depths and working distance increases from the shafts.

Whether relevant to gold mines or the mining industry as a whole, the research presented can add value to future ventilation and cooling strategies applied by mine operators to create an underground working environment that can promote a safe and productive work environment for employees. The research also identified the shortcomings of ventilation and cooling methods currently being implemented in deep-level gold mines. Thus, assisting to close the gap between already identified means of conducting underground ventilation and cooling and the actual application and management of ventilation and cooling strategies on South African deep-level gold mines.

The research can be used to highlight the concerns that specialists have in connection with these high temperatures and cooling methods that are selected. It is very important to note that although the research was conducted in the Free State this does not imply that it should apply only to this area.

For example, one mine in the West Wits Carletonville area is only able to mine 5 km along strike direction from the shaft and is currently unable to mine the mineral resources located 5 km to 7 km from the sub-vertical shaft. The results of this research may enable this mine to access these areas to increase the Mineral Reserves and to extend the life of the mine.

1.11 Study Outline

Chapter 1 provided a background of the research, an overview of the research statement and problem, and presented the objectives of the research. The research questions as well as the significance of the research were also presented in this chapter. **Chapter 2** provides a literature review. It outlines the importance of providing sufficient ventilation and cooling in the underground working environment to improve productivity and safety. It also expresses the viewpoint of other researchers. **Chapter 3** of the dissertation deals with the cooling methods researched through mixed methods of both qualitative and quantitative techniques. **Chapter 4** investigates the ventilation and cooling methods adapted at Mines A, B, C, and D (case studies), also putting into consideration the results obtained from the interview process, and the study of ventilation reports. **Chapter 5** portrays the interpretation of findings and results. It also looks at benchmarking and analysis of the findings and results obtained from previous chapters. In this chapter, recommendations are provided, and conclusions are discussed.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to the Literature Review

The review of the literature has been focused on several areas, for example, the study of the source of heat, acceptable underground environmental standards for employees both locally and internationally, the study of heat stress, and proposed cooling methods used underground.

The mining sector has proven to have one of the most challenging working conditions. That is why the environmental conditions, i.e. effective temperature (ET) have been managed and maintained within an acceptable range to avoid the exponential rise in occupational hazards and operating costs (Massanés, et al., 2015).

Based on previous research conducted by Schutte & Franz (2000), a decrease in productivity was noted in the hot, humid underground mines of South Africa for heat-acclimatised workers doing intensive physical work. Heat acclimatisation refers to biological adaptations that reduce physiologic strain (e.g. heart rate and body temperature), improve physical work capabilities, improve comfort, and protect vital organs (brain, liver, kidneys, muscles) from heat injury (Jackson & Rosenberg, 2010). Jackson and Rosenberg (2010) recorded a decrease in productivity beginning at an ET of 27.7°C (wb) (at 100% relative humidity with minimal air motion), which is approximately the reported threshold for the onset of heat stroke during hard work. These observations display the importance of the effective temperature or corrected effective temperature (CET), as a heat stress index in mines where the humidity level is high (Jacklith, et al., 2016). Ventilation is a costly component of mining. Not only in terms of the money spent to operate fans or providing cooling but also there are safety and productivity correlations when wet-bulb temperatures are reduced from 30.5°C to 28.5°C (wb). According to Smith (1988), a decrease in the injury rate was recorded from 41.8 to 16.3 incidents per thousand employees per annum, and productivity (tonnes/worker/month) increased by 40% with the reduction in the wet-bulb temperature.

Biffi (2018) comments that each underground working must be mechanically ventilated with a framework that is designed, installed, and operated and kept in good working conditions as per best engineering practice. Ultimately a ventilation system should provide adequate air to the underground workings. Past research on ventilation and cooling demonstrates that adequate central ventilation and cooling research work has been done and that the mining industry is currently at a phase where past work should be reviewed, and recommendations appropriately implemented.

Department of Mineral Resources (2002) highlights that for heat-unacclimatised individuals' ET or CET values that exceed 30°C (wb) for sedentary activities, 28°C (wb) for moderate work, and 25.5°C (wb) for hard work are unacceptable for workers. For fully heat-acclimatised individuals, the recommended limits are increased by about 2°C. Marriott (1993) emphasises that it is especially true when people participate in hard physical work, the body competes for the blood to supply the essentials organs and at the same time to cool the body itself. This occurs when the nerve centre recognises that the body temperature is extremely high, and it sends impulses that cause veins, providing the vessels in the skin, to expand. This process is called vasodilation and occurs in shallow veins of warm-blooded creatures when their surrounding condition is hot; this procedure occupies the stream of warmed blood to the skin of the creature, where the heat can be discharged with ease to the climate.

It remains essential that temperatures in underground excavations be as sufficiently low as is possible so that the people working there are not at risk. This is carried out by designing the ventilating systems of a mine so that sufficient ventilating air flows through each and every excavation to absorb and carry the heat out of the mine. It is important to understand that at extreme depth, large volumes of air alone are not adequate to achieve this. The air must be chilled in order for it to sufficiently cool the underground environment (McPherson, 2012).

2.2 The Objectives of Underground Ventilation

The basic target of an underground ventilation system is clear and straightforward. It is to provide airflows in the correct quantity and quality to dilute contaminants to safe concentrations and provide cooling in all parts of the operation where personnel are required to work or travel. This essential requirement is incorporated into mining law in countries that have such legislation. How "quantity and quality" are defined differs from country to country depending upon their mining history. The general requirement is that all persons must be able to work and travel within an environment that is safe, and which provides reasonable comfort. An interpretation of the reasonable comfort requirement depends greatly on the geographical location of the mine and the background and expectations of the workforce.

The method of controlling atmospheric conditions in the subsurface is airflow. This is delivered, principally, by main fans that are usually, but not necessarily, located on surface. In some instances, regulations may demand that main fans are sited on surface for gassy mines. While the main fan, or a combination of main fans, handles all of the air that circulates through the underground network of airways, with underground booster fans serving specific ventilation districts only. Auxiliary fans are used to pass air through ducts to ventilate blind headings. The distribution of airflow may also be controlled by ventilation doors, stoppings, air crossings, and regulators (McPherson, 2012).

It is frequently the case that it becomes impracticable or impossible to contend with all environmental hazards through the use of ventilation alone. For instance, the increases in air temperature brought about by the compression of the air in the downcast shafts of deep mines may result in that air being too hot for the workers even before it enters the workings. No practical amount of increased airflow solves this issue (i.e. auto-compression). Solutions include the ancillary control measures that may be advisable or necessary to supplement the ventilation system to maintain acceptable conditions underground.

The design of significant underground ventilation and environmental control system is a complex process with many interacting features. The principles of systems analyses ought to be applied to guarantee that the outcomes of such interaction are not ignored. In any case, ventilation and the underground environment should not be treated in separation during planning exercises. They are an integral part of the overall design of the mine or subsurface facility.

It has often been the case that the types, numbers, and sizes of underground machinery, the required rate of mineral production, and questions of ground stability have dictated the layout of a mine without, initially, taking the demands of ventilation into account. This brings about a ventilation system that may lack effectiveness and, at best, be more costly in both operating and capital costs than would otherwise have been the case. A typical blunder has been to size shafts that are appropriate for the hoisting duties but inadequate for the long term ventilation requirement of the mine. Another frequent, related problem is a ventilation infrastructure that was adequate for an initial layout but lacks the flexibility to handle fluctuating production demands for the mineral. Again, this can be very expensive to correct. The consequences of inadequate ventilation planning and system design are untimely cessation of production, high costs of reconstruction, poor environmental conditions, and, still too often, tragic consequences to the health and safety of the workforce. It is, therefore, most significant that ventilation engineers should be incorporated as a necessary part of the design team from the initial stages of planning a new mine or other underground facilities (McPherson, 1964).

2.3 Defining Sources of Heat

Many different heat sources contribute to hot environmental conditions underground. These factors may be greatly increased or decreased based on the mine and mining methods used (Ryan, 2017). Some are major contributors of heat addition to air and some are minor. Some of them are unavoidable, while some of them require utilisation of proper techniques for their reduced effect (Leveritt, 1998).

The major sources of heat in underground mines are:

- Strata heat;
- Auto-compression;
- Machinery and lights; and
- Underground water.

The minor sources of heat in mines include:

- Human metabolism;
- Oxidation;
- Blasting;
- Rock movement;
- Pipelines; and
- Energy losses in airflow.

Radiant heat from the sun and rock face account for a large proportion of the heat affecting miners working in opencast mining operations. Mines located in tropical areas have the additional burden of high humidity to add to the heat load. By far the greatest problems of heat stress have been traditionally associated with underground operations since the heat is confined to the working area. If proper care is not taken the temperature of the working area can increase to an uncomfortable level (Leveritt, 1998).

Heat is an integral part of all the mining activities. Not only activities but different conditions are also responsible for the emission of heat in an underground as well as opencast mine. The main function of ventilation is to dilute and remove gases and dust as well as provide oxygen and to remove heat (Carpenter, et al., 2015).

Underground temperatures are a result of the heat inputs, produced either naturally or by the exploitation process itself. It has recently become a matter of great concern because it determines the running of the mine, affecting safety issues and efficiency rates (Massanés, et al., 2015). There are various sources of heat in mining, however, this research explains four main sources due to their significant impact on the accumulation of underground heat in the mine:

- Geothermal gradient;
- Heat transfer from rock strata;
- Mining equipment; and
- Explosives.

Besides the above stated factors, there are other possible factors like ground water or broken rock carried along the airways that can also have a significant contribution. Depending on the mine, the input of each part varies due to its specific characteristics. Figure 2-1 shows the heat inputs percentage contribution in a case study by Payne (2008) where auto-compression was a major contributor with 51% and groundwater being the least contributor with 3%.

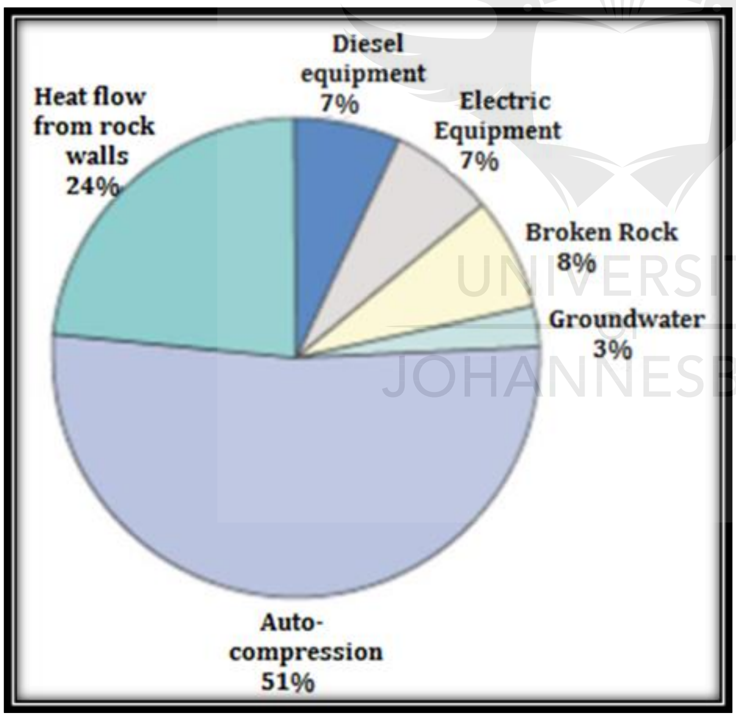

Figure 2-1: Heat contributor in a metal mine, case study (Payne, 2008)

The essential parameter in characterising the geothermal gradient is the virgin rock temperature (VRT). VRT is a component of surface rock temperature and depth, and it varies from region to region. An indication of the virgin rock temperatures, at particular depths, in certain components of South Africa, is shown according to (Mochubele, 2014) and the formulae for calculating VRT for these areas can be summarised as in Table 2-1.

Table 2-1: Virgin Rock Temperatures at depth.

MINE	FORMULA	EQUATION #
Witwatersrand:	$VRT=18+(9.3\times d)$	Equation 1
Carletonville:	$VRT=16+(10.5\times d)$	Equation 2
Free State:	$VRT=20+(14.5\times d)$	Equation 3
Bushveld Complex:	$VRT=18+(20\times d)$	Equation 4

(Mochubele, 2014)

2.3.1 Geothermal Gradient

The geothermal gradient is the rate of change of temperature with depth in the earth or the increase in strata temperature with depth. The geothermal flow of heat coming from the earth's core and passing through the earth's surface has a mean value of 0.05 to 0.06W/m^2 (McPherson, 1992). In utilisation, it is far frequently inverted to give integer values and is then referred to as the geothermal step, calculated as shown in Equation 5 (McPherson, 1992).

Equation 5

Geothermal step = $dD/d\theta$, and units are m/°C

Where:

- dD=change in distance; and
- $d\theta$ =change in temperature.

In the underground mine, when air goes through an airway, its temperature typically increases. Due to the natural geothermal heat being conducted through the rock towards the airway, then passing through the boundary layers that exist in the air close to the rock surface. Van den Berg *et al*. (2013) assure that this heat transmission is often greater in working areas where rock surfaces were freshly exposed (e.g. production blast), where the rock surfaces are often warmer than the air.

Nonetheless, these rock surfaces gradually cool in time to reach an equilibrium point, where the temperature of the rock surface is only a fraction of a degree centigrade higher than the temperature of the air. The amount of heat transferred to the air from the strata is also a component of depth. As one advances downwards through a progression of geological formations, the geothermal step differs according to the thermal conductivity and diffusivity of the local material. The age of the rock, its thermal properties, and its proximity to recent igneous activity can all affect the geothermal gradient. Even within a single mining district, it can vary and seldom be considered a constant value (Kocsis, 2009). Although the surface temperature varies considerably (day to night and summer to winter), the VRT is fairly constant (at a given depth) at depths of 20m to 30m or more. Figure 2-2 shows clearly that at a depth of 2000m or more, the VRT exceeds 45°C in most of the mining areas of this country. The VRT in ultra-deep (>3500m) mining is more than 75°C for the Free State and Bushveld Complex whilst Klerksdorp approaches 70°C.

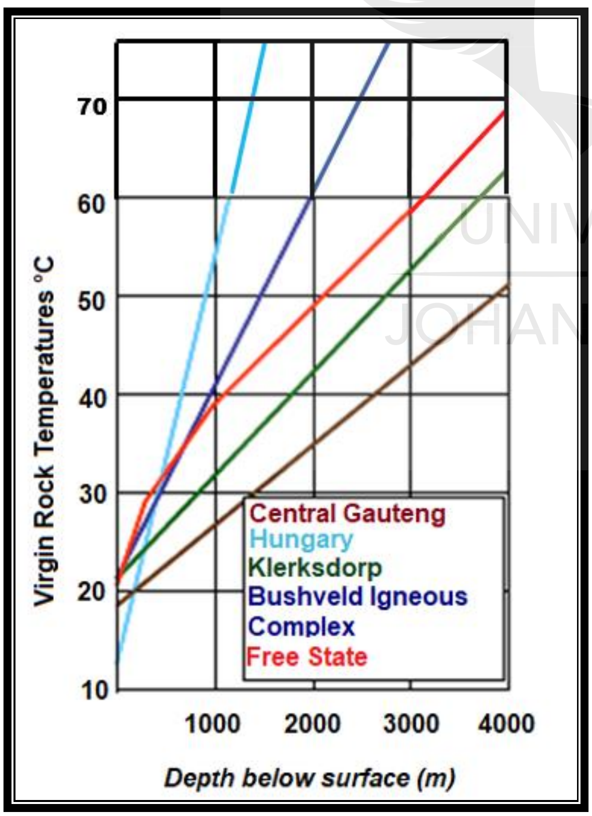

Figure 2-2: VRT as a function of depth adapted from (McPherson, 2012).

2.3.2 *Heat Transfer from Rock Strata*

Strata heat is known to be one of the main sources of underground heat. It refers to the heat emitted from the surrounding rocks and getting added to the mine atmosphere. Subsurface rocks mainly have their heat reserved in-situ, which emits heat that gets transferred to the upper part of the earth (mantle and crust) (Sunkpal, et al., 2018). Hence strata heat is a factor to be considered while planning ventilation systems.

2.3.3 *Mining Equipment*

During mining, electrical, and diesel-powered equipment are used and most of the energy consumed is converted into heat. The equipment converts electrical and diesel into heat, directly through power losses and indirectly through friction when doing actual work (Burrows, et al., 1982). Mining equipment is one of the major sources of heat in South African mines as the use of equipment is on the increase across the mining industry. Diesel equipment emits more heat than electrical equipment. It is estimated that diesel produces three times more heat than electrical equipment due to its overall efficiency of around 30% (Burrows, et al., 1982).

Canadian mines, increased mechanisation thereby increasing power demands which have resulted in the realisation that such underground equipment being considered as one of the major sources of heat. The total heat produced is equivalent to the rate at which power is supplied.

Additionally, Kocsis (2009) arrived at the fact that almost one-third of the heat generated by diesel machinery becomes noticeable as heat from the radiator and machine body, one-third as heat in the exhaust gases, and the remaining one-third as useful shaft power, which is also turned into heat through frictional processes. A major difference between diesel and electrical equipment is that diesel equipment gives rise to part of their heat output in the form of latent heat. Equipment testing carried out in underground mines has proven that the litres of water emitted per litre of fuel consumed may range from 1 to 10 litres, depending upon the diesel engine's cooling system and emission control devices. The diesel engine aspirates a constant volume of air and delivers power in proportion to the amount of injected fuel and engine speed. At constant speed, the volume of exhaust gas is nearly constant for all load conditions and, when the fuel injection rate is suitably controlled, very little carbon monoxide is produced. Compared to the gasoline engine, it aspires to a fuel-air mixture of nearly constant composition and delivers power in proportion to the amount of throttled mixture reaching the cylinders and engine speed. The volume of exhaust gas increases as power output increases is approximately constant in composition and always contains dangerous concentrations of carbon monoxide (Burrows, et al., 1982).

Safety with mobile diesel-powered equipment in mines and tunnels depends chiefly upon proper adjustment and maintenance of the engine, suitable rapid dilution of the exhaust, and adequate positive mechanical ventilation to dilute and remove the exhaust from the mine and to restore oxygen used in the combustion process.

Therefore, the operation of diesel equipment with insufficient ventilation should be discouraged vigorously. All diesel equipment should be shut down immediately when positive mechanical ventilation is interrupted for any reason to reduce exposure to diesel particulate matter.

The quantity of normal air necessary to dilute a particular constituent of diesel-exhaust gas to the safe hygienic concentration can be determined with close approximation from the basic rational relation using Equation 6 (Holtz, 1960).

Equation 6:

$$Q = V * \frac{c}{y}$$

Where:

Q is the volume of normal air required for ventilation (cubic feet per minute);

V is the volume of exhaust gas produced by the engine (cubic feet per minute);

c is the concentration in the exhaust gas of the particular toxic constituent under consideration (percent by volume); and

y is the maximum safe hygienic concentration for the particular toxic constituent under consideration (percent by volume).

Results from several operating conditions must be explored by trial to determine which toxic constituent requires the greatest volume of normal air for satisfactory dilution. The maximum volume determined anywhere in the operating range of the engine is then multiplied by two to find the safe ventilation rate in mines and tunnels.

2.3.4 Explosives

Explosives contain chemical energy that is converted into heat during the blasting process and can be considered as one of the significant sources of heat. It has been estimated that about 90-95% of the heat enters the broken rock and is released over a long period (Mauryaa, et al., 2015); (Burrows, et al., 1982). A portion of the heat generated from a blast is dissipated with blasting fumes, when an explosion occurs a peak heat load onto the ventilating air follows. Incandescent particles from blasting operations may contain sufficient heat energy to ignite dry wood or combustible waste material. The remaining heat after blasting is stored within the fragmented rock. The amount of heat stored inside the broken rock can depend upon the extraction method (Kocsis, 2009).

2.3.5 Auto-Compression

Auto-compression occurs when the potential energy is converted to thermal energy. When the surface air is sent down the workings, either naturally or through man-made ventilation, it experiences a compression. This means that although the volume of air while going down reduces, the amount of heat remains the same resulting in hotter air. Thermodynamically, this phenomenon is the same as the way gas reacts in a compressor, air entering through a mine through a shaft is compressed and heated as it flows in a downward direction. If there is no interchange in the heat or moisture content of the air in the shaft, the compression takes place adiabatically, with the attendant temperature rise following the adiabatic law (Mauryaa, et al., 2015).

The temperature increase due to auto-compression can be up to 10°C per kilometer of vertical depth, whether in a shaft or in a decline. The heat from air auto-compression would be more significant in deeper mines as it increases with the vertical depth. Also, it is obvious that mines sunk in hot areas are hot work sites due to the effect of hot surface air combining with the auto-compression (Ramsden, et al., 2001).

2.4 Acceptable Environmental Standards for Employees

The human body has very complex and very effective heat regulating mechanisms that strive to keep the body temperature constant at around 37°C. To accomplish this balance requires a constant heat exchange between the body and its environment. The amount of heat that must be exchanged is a function of the total heat produced by the body (metabolic heat) and the heat picked up from the environment (McPherson, 2012).

Defining a thermally acceptable environment has recently been debatable, previous studies carried out on workers found that the rejection temperature of 27.5°C wet bulb (wb) was adequate for a healthy working environment (Burrows, et al., 1982). The rejection temperature was based on the heat stress limit for essentially nude un-acclimatised men working in the gold mines (Burrows, et al., 1982). Acclimatised workers can work up to a temperature of 34°C (wb) depending on the metabolic rate of work, see Table 2-2 for details.

Table 2-2: Maximum air temperatures for various work rate.

Metabolic Rate of Work	**Maximum wet bulb temperature for acclimatised men (°C)**
Hard Work	32.5
Moderate	33.0
Light Work	34.0

Adapted from (Le Roux, 1990).

It is crucial when establishing rejection temperatures to evaluate the productivity of employees. Figure 2-3 demonstrates the relationship between temperature and productivity. To interpret the graph, it is also important to understand that the cooling power of the air also depends on the speed of the air.

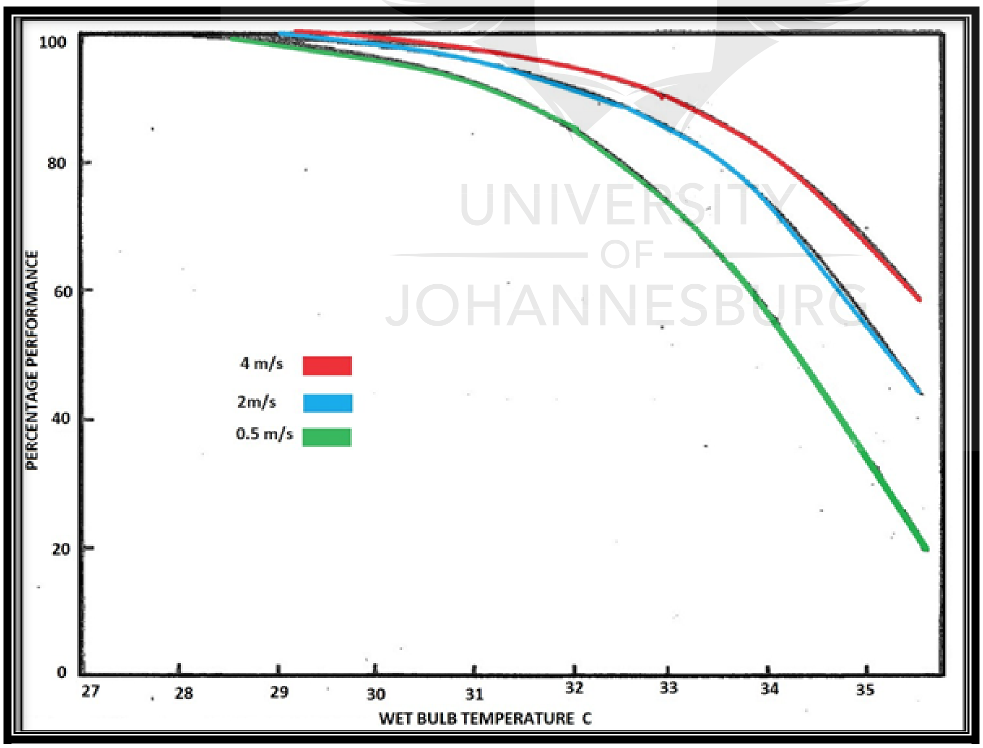

Figure 2-3: Performance vs Wet Bulb Temperature (Le Roux, 1990)

Figure 2-3 denotes that when workers are exposed to underground conditions, the rejection temperature of 27.5°C (wb) enables both acclimatised and unacclimatised workers to perform at 100% performance. The performance of workers decreases when the wet bulb temperature reaches 30°C (wb) and is exponentially negatively affected when the temperature is above 32°C (wb). Mochubele (2014) suggests that maintaining rejection temperatures of working areas below 27.5°C (wb) comes at an unreasonable cost given the electricity price hikes. In contrast, most mines carefully choose a ventilation strategy that sets the rejection temperature at the upper scale, in a range of 28°C to 29.5°C (wb) as this is less expensive to achieve than aiming for the 27.5°C (wb). Note the considerable decrease in performance when the temperature equals or exceeds 31°C (wb).

South African mines are required to draft and implement a mandatory Code of Practice (COP) based on guidelines established by the chief inspector of mines in terms of Section 9.2 of the Health and Safety Act. The mandatory thermal stress COP is summarised in Table 2-3, it shows temperature ranges, interpretation, and actions required (Department of Mineral Resources, 2002).

Table 2-3: Thermal stress Code of Practice (Department of Mineral Resources, 2002)

Category	Temperature range (°C)	Interpretation	General Action
A	twb >32,5	Abnormally hot. Unacceptable risk of heat disorder	Risk assessment required to do the work
B	29 < twb ≤ 32.5	Potential heat disorder	Heat stress Management (HSM) mandatory
C	27.5<twb≤ 29	Economic range for acclimatised workers	HSM mandatory
D	twb ≤ 27.5	Risk of heat disorders is minimal for both un-acclimatised and acclimatised workers	No special precautions. Temperature monitoring

The mandatory COP on thermal stress is a measure to limit exposure of employees to hot environments to avoid the risk associated with heat related hazards. In the South African context in mines, a hot environment means any work environment where the dry-bulb (db) temperature is higher than 37.0°C, or where the wet-bulb temperature is higher than 27.4°C (Schutte, et al., 1994). Additionally, considering women in mining, as women are now getting more involved in working in underground conditions it remains essential so as to ensure safe working conditions for them (Zungu, 2011).

2.5 Hazards of Heat Stress

The combination of all internal and external body heat factors which cause the body to become stressed is called heat stress. Internal factors that determine the level of heat stress on the body include core body temperature, acclimatisation, natural heat tolerance, and metabolic heat generated by the workload. The external factors being the surrounding air temperature, radiant heat, air velocity, and humidity. Besides heat reducing the productivity of workers, it also has a negative impact on their health and safety. Various illnesses may occur when workers are subjected to high levels of heat stress and it is crucial to be able to identify the signs and symptoms of these illnesses (Burrows, et al., 1982), so that preventative measures can be put in place.

An experiment was carried out by Schutte & Franz (2000) where they considered the potential relationships between the thermal conditions, specifically the stope-face wet-bulb temperature, firstly, the rate of reportable injuries and lastly the production rate. Data were obtained from two standard sources, namely the Chamber of Mines Death and Injury Rate Tables and the Chamber of Mines Annual Ventilation Reports. The analyses considered information from all monitored gold mines from 1987 to 1994, involving a total workforce of nearly a million mine workers (975 265). In further analysis, the average stope-face wet-bulb temperature and production rates of these workers with the highest rates of reportable injuries were compared with those of the workers with the lowest reportable injury rates. Table 2-4 summarises the results from the industry-wide comparison.

Table 2-4: Reportable injury rate for various ranges of wet-bulb temperature (Schutte & Franz, 2000)

Mean stope-face wet-bulb temperature (°C)	Mean injury rate (n/1000)
25,0 – 25,9	22,63
26,0 – 26,9	24,04
27,0 – 27,9	24,18
28,0 – 28,9	23,70
29,0 – 29,4	26,61
29,5 – 29,9	26,13
30,0 – 30,4	26,80
30,5 – 30,9	26,45
≥ 31,0	27,89

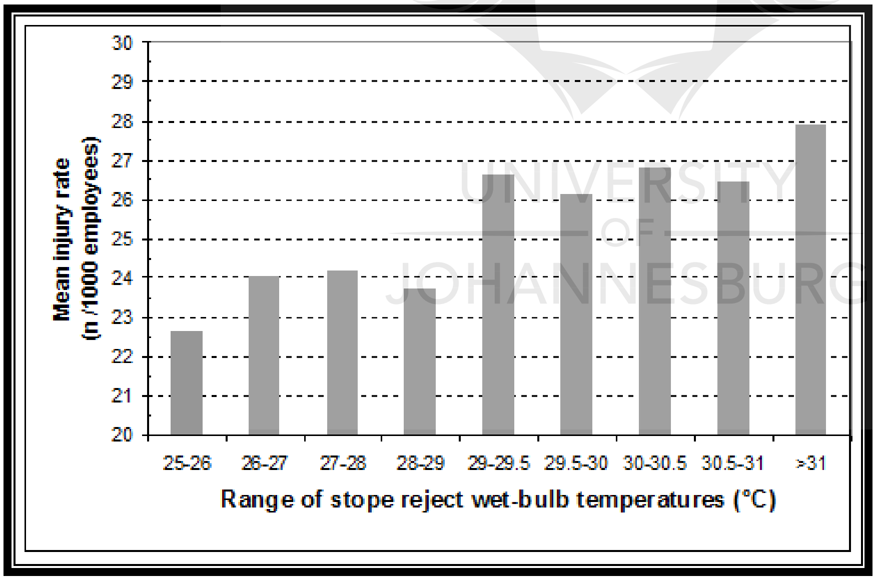

Figure 2-4: Mean reportable injury rate for various ranges of wet-bulb temperature (Schutte & Franz, 2000).

The mean values presented in Table 2-4 and illustrated in Figure 2-4, indicate the possibility of an association between mean stope-face wet-bulb temperature and mean reportable injury rate, with a noticeable increase in the latter occurring from 29°C (wb) upwards. Schutte & Franz (2000) affirm that heat increase above 29°C (wb) can negatively affect safety and productivity because of physiological effects such as loss of concentration and errors of judgement. As such, Schutte & Franz (2000) advised on the importance of maintaining a core body temperature within narrow limits of around 27°C (wb) to prevent brain dysfunction. In the study, they found that workers can perform at 100% of the production capacity at a 25°C (wb) temperature but drops to 70.2% at 32°C - 33°C (wb) temperature.

2.6 Signs and Symptoms

Heat stress combines a progression of conditions where the body is under stress from overheating. Heat-related illnesses include heat cramps, heat exhaustion, heat rash, and heat stroke. Symptoms can differ from excessive sweating to dizziness, cessation of sweating, and collapse (Pradyumna, et al., 2018). People with medical conditions, such as heart disease are at the greatest risk of heat stroke. However, even young, and healthy individuals can succumb to heat related sicknesses if they engage in physically demanding activities under hot environmental conditions.

The Iowa State University, Environmental Health and Safety further elaborates that certain behaviors can also put people at greater risk such as drinking alcohol, participating in strenuous physical activities under hot temperatures, and taking medications that impair the body's ability to regulate its temperature or that hinder perspiration. It can, therefore, be concluded that heat stress can be prompted by high temperatures, heavy workloads, and clothing inappropriate for the heat and humid environment.

The indications of heat stress are often overlooked by the victim because the process is gradual. The individual may initially be confused or incapable to concentrate, followed by more severe symptoms, such as fainting and/or collapsing. If heat stress symptoms occur, it is recommended to move the victim to a cool, shaded area, provide water to drink, and immediately contact a supervisor or another individual to assist (Mandal, 2019).

2.7 Heat Disorders

Heat disorders are a group of physically related illnesses caused by prolonged exposure to hot temperatures, restricted fluid intake, or failure of temperature regulating mechanisms of the body. Disorders of heat exposure include heat cramps, heat exhaustion, and heat stroke (also called sunstroke). Heat exhaustion occurs as a result of a decrease in the volume of blood being circulated. This decrease is frequently credited to either a salt deficiency (inadequate dietary intake) or to dehydration (sweating with inadequate water replacement). Since a normal western diet provides more salt than that lost through sweating, in most cases heat exhaustion occurs as a result of dehydration. In some cases, it may occur completely independently of dehydration as a result of improper distribution of the circulation during heat stress. People that suffer from some form of circulatory insufficiency are more likely to experience heat exhaustion (Burt, 2016).

Heat collapse is also known as fainting is the most frequently observed heat disorder. It is a minor disorder brought about by the pooling of the blood in dilated vessels of the skin and lower part of the body. This pooling results in a reduced return of blood to the heart and hence to the brain. Recovery from this state occurs rapidly once the patient gets the chance to lie down. Intermittent activity helps to prevent the occurrence of heat collapse (Lundgren, et al., 2013).

Research demonstrates that the cause of heat cramps is complex and involves various factors that affect the body's electrolyte balance. Prevention of heat cramps can be achieved by ensuring that an optimum state of hydration exists. Treatment ought to include the administering of fluid, but the fluid should not have a salt concentration of more than 0,1% (1gram/liter). Severe cases should be sent to the hospital for treatment (Mandal, 2019).

A heat rash, known as prickly heat, may occur in individuals who experience no relief from hot humid heat stress. It is brought about by sweat being consistently present on the surface of the skin. This leads to a swelling of the skin cells surrounding the sweat ducts, which then become blocked and inflamed. It is potentially dangerous in that it causes a decreased sweat rate, which could in turn lead to heat stroke. It is prevented by providing cool conditions for people between bouts of heat exposure. Although less severe than the heat illnesses described above, heat fatigue has important consequences in practice, and it is thus a heat disorder worthy of specific mention. Heat fatigue may be transient or chronic (Mandal, 2019).

Transient heat fatigue applies to momentary impairment in human performance that occurs during heat stress. It is a result of heat strain and in particular a perceived discomfort. In a hot work place, the adverse effects of transient heat fatigue provide an obvious incentive for improving environmental conditions. Chronic heat fatigue applies to long term impairment in work performance and the social behaviour of people in tropical climates. The degree to which chronic heat fatigue is present in people living in a cool climate and work every day in a hot environment such as mines has not yet been studied (Lundgren, et al., 2013).

Heat stroke does not occur in all individuals in the same way and the diagnosis of heat stroke is not a simple matter. A condition of heat stroke is defined to exist when body temperature has risen such that it causes tissue damage, often of irreversible nature. Although many tissues are damaged in heat stroke, recovery from it depends on the degree of injury to the brain, kidneys, and liver (Mandal, 2019).

Although high body temperature might be viewed as the genuine reason for heat stroke, the length of time that the body is subjected to unfavorable temperature is equally important. The beginning of heat stroke may happen at different body temperatures. The proposal is that anybody with a rectal temperature of 40.6°C or higher be treated for heat stroke. Heat stroke may diminish an individual's heat tolerance. It is therefore important that recovered people be tested for heat tolerance before being admitted to hot working environments. The huge significance of prompt and effective cooling is illustrated in Figure 2-5 that shows the percentage mortality in heat stroke victims as a function of their temperature on admission to the hospital (Burrows, et al., 1982). The bold line represents normal rectal temperatures of the patient on arrival at the hospital. At such high rectal temperatures, the death rate of individuals experiencing heat stroke is higher (Lundgren, et al., 2013).

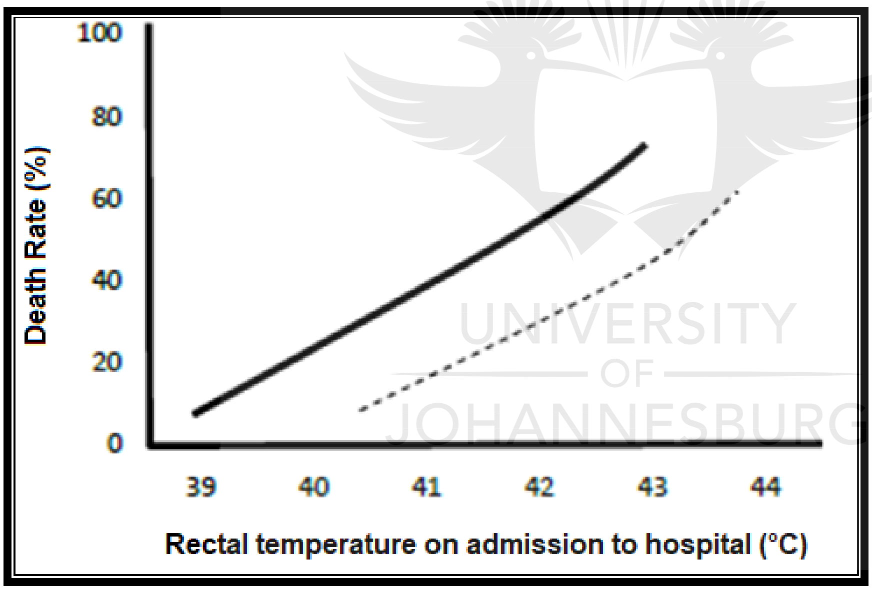

Figure 2-5: Mortality on admission to hospital (°C) (Lundgren, et al., 2013).

2.8 Methods to Reduce the Heat Load of a Mine

To maintain safe temperatures to protect mine workers, mine management must pursue strategies to reduce heat. There are several heat mitigation methods that mine operators can adopt. These incorporate ventilation, artificial cooling, and reducing the magnitude of heat generation of a given source (Burrows, et al., 1982). The most well-known technique is using ventilation to supply volumes of cool air to diminish the heat load and dilute the contaminants created in the production workings. This is possible by increasing the fresh air volumes through surface accesses.

If standard ventilation systems are inadequate to provide acceptable climatic conditions in production workings and throughout the mine, artificial cooling methods are often employed. These methods can be exceptionally successful; however, they require intensive capital investments, continuous maintenance, and additional operating costs. These include central cooling, spot cooling, and micro-climate cooling systems. These strategies can be analysed based on their heat reduction, temperatures, and operating costs. Biffi (2018) advises that the opportunities and costs to be secured realised from methods that must be completely comprehended before a mine can execute a heat management programme.

For worldwide discussion purposes, a conventional 'hierarchy-with-depth' for introducing cooling gives a valuable framework. This is shown graphically in Figure 2-6 starting with ventilation only, progressing to surface bulk air cooling, then underground air cooling, and ultimately ice-from-surface systems for the ultra-deep mines.

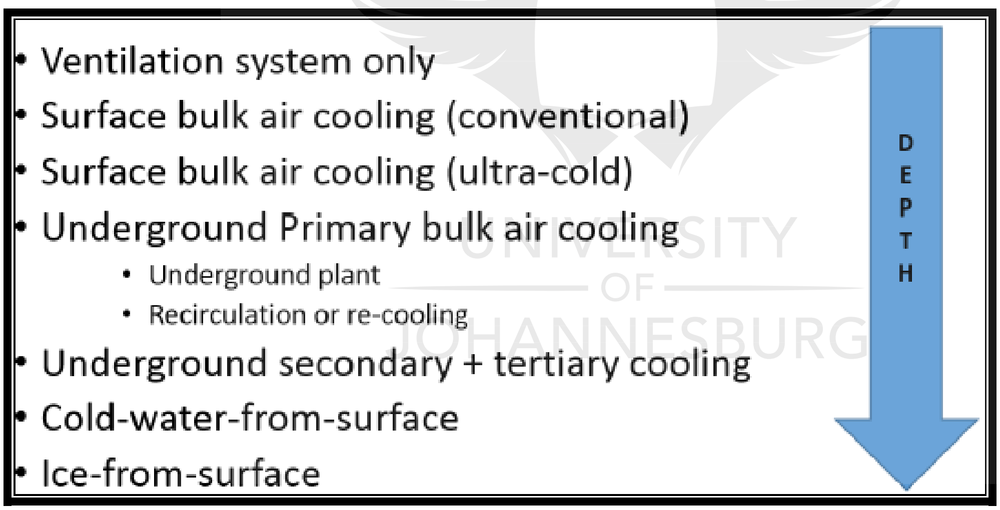

Figure 2-6: Hierarchy of mine air cooling at depth (Ramsden et al., 2007)

The above generic hierarchy of cooling systems as a function of depth, although it is not perfectly valid for all mine sites or operating conditions, it does provide a valuable starting point when designing ventilation and cooling techniques. The choice to select a particular type of system rests on the nature of the risk (Pawinski & Roszkowski, 1985). The ventilation measures and practices differ according to the type of mine, and the mining methods in use. Normally, the ventilation of shallow underground mines, regardless of the type of mine and mining method, is divided into two broad branches, the primary ventilation, and secondary or auxiliary ventilation systems. The primary ventilation is accountable for the total volume flow through the mine and is planned based on the pressure, size, complexity, equipment used, production rate, etc. The auxiliary ventilation is responsible for the ventilation of the development ends, production zones, and facilities disconnected from the main circuit, that is, where there are no sufficient ventilation connections (Van den Berg, 2013).

Some heat sources can be addressed or minimised while the impact of others may just be reduced by the introduction of some external intervention. The heat from machines can be managed by introducing more efficient machines and the heat from fissure water can be addressed by stopping the inflow of water into excavations or containing the water or pump the water out of the work area.

The two major sources, geothermal heat and auto compression cannot so much be decreased, and therefore it is inevitable that depth reaches where it becomes necessary to cool down the ventilating air through refrigeration to maintain acceptable temperatures in the underground workings (Leveritt, 1998).

2.8.1 Insulation

If the heat source can be insulated the rate of heat flux is reduced. This is done in two ways according to (McPherson, 2012), that is insulation of fissure water, stopes, and tunnels which are discussed in the following subsections.

2.8.1.1 Insulation of Fissure Water

The flow of heat from fissure water to the ventilating air must be reduced and this is done by conveying this water in insulated pipe columns. The main consideration here would be the cost of the insulated pipes compared to the saving in refrigeration that may result from their use. This option is probably only viable where a large volume of water has to be contained in this way (McPherson, 2012).

If nothing is done to improve chilled water pipe insulation systems, over time the arriving chilled water temperatures in the working sections of mines will increase from an operational norm of 10°C to a norm of 13°C (Rawlins, 2007).

Service water mine service water refers to water sent underground and used for general services such as cooling of machinery, cooling of air, dust suppression, stope cleaning, etc. Mine service water may be chilled or unchilled. Fissure water is a common mining term in hard rock mines that refers generically to groundwater that enters the mine. The fissure water typically contains relatively high concentrations of salts, which have been leached from the rock. When this mixes with the spent service water, the net result is a deterioration in water quality underground (Pulles, 2008).

2.8.1.2 Insulation in Stopes and Tunnels

The area of an exposed rock face from which heat can flow into the stopes is significantly reduced by the placement of back fill. Although back fill is primarily employed as regional support, it has the additional benefit of insulating some portion of the geothermal heat source. The other major benefit is that the ventilating air is contained within the face area, where most of the activities and workers are concentrated. Short-circuiting of air is greatly reduced as the backfill creates strike and dip ventilation walls. The backfilling strategies often make use of the waste rock or tailings that are considered by-products of the mining operation. This is an effective means of tailing disposal because it negates the need for constructing large tailing dams at the surface. The backfilling of underground voids also improves local and regional stability, enabling safer and more efficient mining of the surrounding areas (Sivakugan, et al., 2006).

The cladding of tunnel walls by spraying them with an insulating substance may greatly reduce the heat flux from them. Even shotcrete and gunite cladding has this effect as the thermal conductivity is lower than that of the rock mass. In a thesis carried out by Liu (2013) on the use of shotcrete both as a structural lining and as effective thermal insulation to reduce the heat load on the ventilation and cooling system within such tunnels. Results showed excellent heat load reductions in both full and partial insulations, with the developed shotcrete (Liu, 2013).

An improvement in arriving water temperature of 1°C is easily attainable if good total insulation systems are used, but improvements of at least 2°C and more should be aimed for. With the present estimated cost of insulation at around 5% of the capital cost of a refrigeration system, the justification for good and maintained insulation is self-evident (Rawlins, 2007).

2.8.2 Machinery

The heat load resulting from the use of machinery cannot be significantly reduced by improving the efficiency of the machines. Proper planning and management of equipment can, however, make a huge difference. Important aspects to consider here are (Wagner, 2013):

- Appropriate equipment selection (electric vs. diesel) where possible,
- Placing of equipment – keep "hot" machines away from intake airways,
- The concentration of machines into a small area (management of machines).

2.8.3 Increased Ventilation

With the ever-increasing depth of mines, the management of heat has become a key issue for their design and operation. If the volume flow rate of ventilating air is increased, it will provide a bigger cooling effect. This might present a solution at shallower depths where auto compression does play a major role (Wagner, 2013).

The practice of ventilation is continually evolving with new technological advances developed in the mining industry. In recent years the advances in diesel engine technologies, ventilation modeling software, and ventilation management capacities have redefined the historical methods used to evaluate systems (Wallace, et al., 2015).

2.8.4 Refrigeration

Ultimately, the only solution may be to lower the temperature of the ventilating air using refrigeration. The air is cooled either on surface before it enters the mine or underground at the bottom of the downcast shaft. In deeper mines, secondary cooling (and even tertiary cooling) may be required. These processes were discussed later.

There is a need to plan refrigeration requirements based on the lowest arriving chilled water temperatures possible to minimise the amount of chilled water circulated and, thus, the size and cost of refrigeration plant and infrastructure (Rawlins, 2007).

2.8.5 Chilled Service Water

The use of chilled service water is a common practice in many mines in South Africa and it is usually done in conjunction with refrigeration. Water is cooled down in the refrigeration plant and a portion of it is used to cool down the air in Bulk Air Coolers while the rest is used as service water in the working places. The use of chilled service water has a significant cooling effect in a working place (McPherson, 2012).

2.9 Primary Ventilation Planning

Ventilation planning addresses two main phases in the life of the mine. The initial stage is for a new mine when no real structure is in place. At this time, the ventilation design bases on the production rate, mine infrastructure (geometry), and consumers. McPherson (2012) depicts ventilation as an essential method to remove heat from the underground mine environment. Air is important not only for breathing but also to disperse chemical and physical contaminants (gases, dust, heat, and humidity). This used air, otherwise called return air or contaminated air is then led to the surface through the mine's exhausting system. Primary ventilation is associated with the main ventilation and cooling infrastructure. It includes the main surface fans, main booster fans, upcast and downcast shafts, ventilation raises, main airways, bulk air coolers, central refrigeration systems, etc. The point of the primary system is to provide air flow to the working areas in an adequate amount and at proper temperatures and quality (Bluhm & Smit, 2004). The design bases on similar parameters as the first stage. In the second stage, the existing infrastructure influences significantly the design of the new ventilation system. The new design includes the old infrastructure and the limitations imposed by existing fans and stoppings. Air leakages must also be part of this design. Each of the stages activates planning exercises that need to satisfy the criteria imposed by the quality and quantity of the air flowing in the mine (Gherghel, 2010).

Ventilation systems differ from mine to mine due to several factors such as the mining method, ore body geometry, and orientation. Although there is no strict standard across the mining industry, primary mine ventilation design does confirm specific practices. To move air into the underground workings, fans are utilised in explicit configurations such as forcing, exhausting, or push-pull to deliver fresh air into the mine through surface accesses such as shafts, raises, adits, ramps, or other mine entrances. Below are the two critical positions of the fan:

- A surface fan situated at the top of an exhaust shaft or exhaust raise pulls the air hence creating a negative pressure throughout the mine.
- A fan situated at the top of an intake shaft or intake raise compels fresh air through vertical and horizontal airways thus creating positive pressure through the mine.

Surface fans situated at the top of the exhaust and an intake airway would both push and pull the air consequently creating a neutral pressure at some locations in the mine (McPherson, 2012).

The discovery of new mineral reserves that requires expansion beyond the current life of mine or an increase in the production rate likens to an increase in fresh air to dilute the heat load or evacuate other contaminants. The adjustment in ventilation and cooling requirements can require a major upgrade to account for the changes in the mine design. An upgrade such as this creates a higher demand for the ventilation system. Here and there this can be met by upgrading the fans to supply more air. This technique is known as "flooding" (Greth, 2018). The downside to the "flooding" strategy is that the effectiveness diminishes exponentially as the heat load increments. In the end, ventilation loses its economic advantage and must be replaced by artificial cooling (Brake, 2001).

The underground mine environment is very dynamic and needs ventilation planning exercises for any major change in the ventilation system. Most of these major changes are incorporated in the long-term planning for production and are grounded on the life of the mine scheduling. It is incredibly significant to acknowledge that in the planning department there must be two-way communication between the ventilation planning group and production scheduling group as each affects the other. Based on this correlation, there will be multiple solutions and the critical path will be decided based on safety and economics. The analysis could go as far as the entire life of the mine; however, it should only include the foreseeable future (Gherghel, 2010). In some scenarios, the consequences of inadequate planning and ventilation system design deficiencies can result in production losses, high costs of reconstruction, poor environmental conditions, and tragic consequences to the health and safety of the workforce (Kocsis, 2009).

2.10 Refrigeration

High VRT's and the effect of auto compression make it necessary that the ventilating air of a deep mine be refrigerated to ensure that the temperatures in the working of the mine are kept within acceptable limits. The proposed limit of 28ºC (wb) is in close agreement with the wet-bulb temperature range considered to be the acceptable limit for design purposes, namely, 27ºC to 28ºC (Schutte & Franz, 2000).

The wet bulb temperatures in working places depend on a variety of factors, such as:

- Surface air temperature;
- Volume and velocity of the downcast air;
- The wetness of the intake airways;
- Heat added to the air by machinery and people;
- Amount of air reaching the individual working places; and
- The route that the air follows to get there.

When working places become too hot, several of these factors can be altered up to a point to achieve better conditions by actions such as increasing air volumes and drying out intake airways, however, under certain conditions, all these methods fail or become too expensive and then the last resort is to refrigerate the air (McPherson, 2012).

2.10.1 Refrigeration Systems

To provide acceptable underground environment conditions it is essential to estimate the ventilation and cooling requirements at an early stage in the life of the mine as well as when the operation is mature and working far from the shaft (Bluhm & Smit, 2004).

Greth (2018) presumes that mine ventilation has been generally utilised as the primary method to remove the heat and dampness that was transferred to the ventilating air from linear/spot heat sources and diesel/electrical mining equipment. Fresh air is provided into the mine conditions to dispose of the heat and to cool the mine workers. At the point when the ventilation alone cannot satisfactorily provide acceptable working conditions, artificial mine cooling systems are incorporated with the ventilation in the production and development workings and throughout the mine.

Cooling systems are a critical cost, however, the capital and operating costs to install and operate these systems are necessary to ensure the wellbeing of the mine worker. In a discussion with Biffi (2018), he concludes "From my point of view, we just have to spend the money to get the infrastructure if we want to achieve our goal."

However, any increase in the mine's intake airflow can produce a disproportionate increase in power consumption and hence operating costs due to the cubic relationship between the supplied air power and the airflow (Kocsis, 2009). As stated above, due to the unique underground mining environments, cooling system requirements differ from mine to mine according to the mining method, mining rates, depth below surface, distance from the shaft, and other related factors. Cooling system configurations also vary, however, in general, normal ventilation, followed by surface and underground bulk air cooling systems and eventually ice systems is the order in which cooling systems should be implemented.

Mine air can be cooled either on surface before it enters the downcast shaft, underground where it leaves the downcast shaft, or in the working places. In deeper mines, it is common practice to cool the air on surface (surface bulk air cooling), re-cool it when it leaves the downcast shaft (secondary cooling), and cool it again before it enters the stope under the tertiary cooling process (Biffi, 2018).

Surface bulk air cooling is done through a refrigeration plant on surface whereas secondary cooling is done in an underground bulk air cooler that is supplied with cold water either from the surface plant or from an underground refrigeration plant (Mapeta & Rupprecht, 2019). Some installations make use of ice rather than chilled water (the merit of this is discussed later in section 2.13.1).

Figure 2-7 outlines schematically the evolution of a generic air cooling system. Typically, the primary bulk air cooler will be the first component that will be commissioned and used for shaft sinking and initial development of the shaft. The unit is self-contained, with heat energy being transferred to the atmosphere through the condenser cooling tower (CCT). This plant will generate water at 5.0°C. As the mine is extended and production increases the second phase will be introduced to generate water at 1.0°C. This will be used as chilled service or as cooling water distributed to secondary and tertiary air coolers. A precooling tower (PCT) is used to handle the primary feed (usually treated water returned from underground) to maximise the free cooling effect available from the atmosphere. The PCT reduces the water temperature from 28.0°C to about 24.0°C on a hot summer day. As indicated in Figure 2-7, the water enters an underground section along an insulated pipe and is coursed directly into a secondary air cooler. The three-way valve downstream of the cooler drives the demand for cooling through this heat exchanger. This means that during the working shift, the chilled water circulates to the secondary air cooler first and if any is required by mining operations in the stopes or development ends served by this line, then the three-way valve allowed through the passage of the cooler returns water to the face. When the service water consumption in the section downstream of the cooler is reduced or stopped, the excess water is released into a (dedicated) return line. If the return water is kept separate from the drain water, it may report directly to the clear water dam through a separate drain-hole system. At the end of the shift, the system may be shut down totally to limit power usage. At the start of the following shift, the system is reactivated. The process may be automated to allow pre-cooling of the section before re-entry. There is also the possibility of connecting tertiary coolers located in the stopes, effectively utilising the service water rejected from the secondary cooler. If water is produced at 1.0°C on surface it is conceivable (Figure 2-7) that it reaches the stope at about 18°C to 20°C, provided that pipes are insulated, and the system is operated optimally. Water at this temperature may be used effectively for tertiary cooling either directly through a jet spray or indirectly in blast-hole drilling or water jetting (where this takes place) (Biffi & Stanton, 2008).

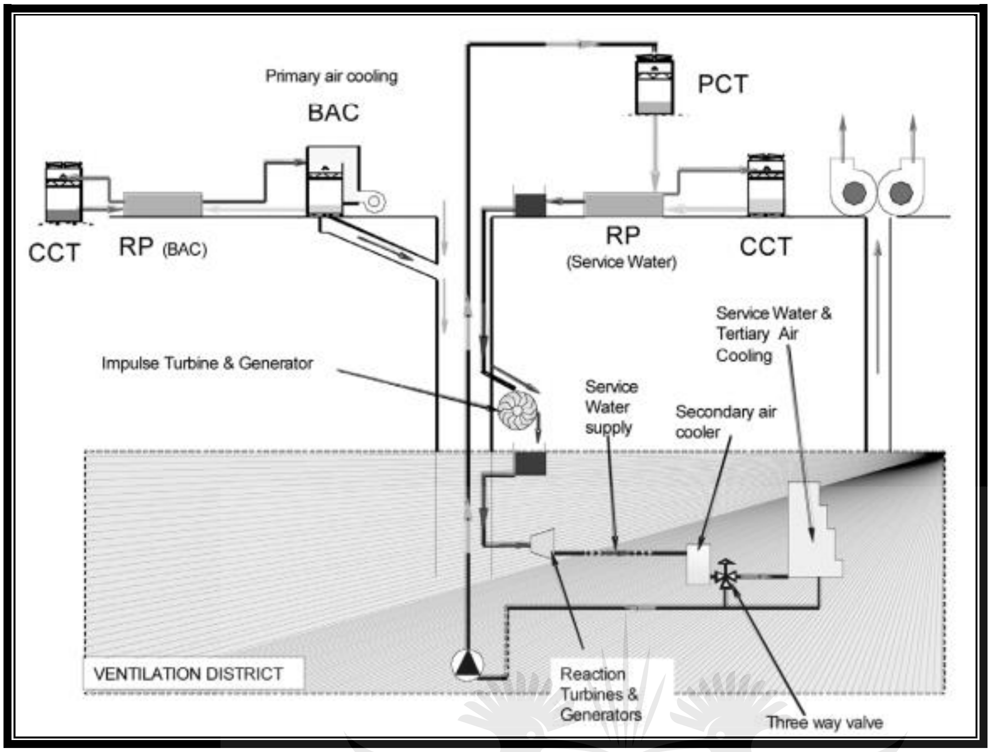

Figure 2-7: Schematic representation of a modern cooling system (Biffi & Stanton, 2008).

2.10.2 Centralised Cooling Systems

Centralised cooling systems are regularly referred to as bulk air cooling or primary cooling. These centralised cooling systems are utilised in mines where heat issues are widespread (McPherson, 2012). Bulk air cooling provides cooling throughout the mine workings to lessen the heat load to safe levels. This cooling system comprises two non-mobile heat exchange systems:

- One is the bulk air cooler, which goes about as an evaporator that cools the encompassing air. The bulk air cooler system incorporates a cooling tower that showers chilled water over the air which is drawn through the bulk air cooler; and
- The other system includes the refrigeration plant, which acts as a condenser where heat is dismissed as air or water to the surrounding area. If heat is rejected through water, then a condenser cooling tower (CCT) is required. In contrast to a bulk air cooler, a CCT rejects the heat from water to the air (Brake, 2001).

Given the location of the bulk air cooler, surface, or underground centralised cooling systems can be broken down into the following two classifications (Liu, 2013).

2.10.2.1 Surface Bulk Air Cooler

This is the primary means of artificial cooling utilised by a mine. It is due to the complexity and cost of implementing underground artificial cooling on a central scale (Mackay, et al., 2010).

A surface bulk air cooler is frequently situated on the surface where the ventilation system can draw air through the chamber of the bulk air cooler. The positional efficiency of a surface bulk air cooler can be the smallest compared to other methods this is because it is located so far away from the mine's production workings. The surface bulk air cooler has no size limit and consequently, it can cool larger quantities of air. Numerous surface bulk air coolers can be utilised in various configurations at the same location to maximise air cooling (Brake, 2001). Two different surface bulk air cooler configurations are shown in Figure 2-8.

Figure 2-8: A vertical fill-packed tower bulk air cooler and multi-stage horizontal spray chamber bulk air cooler (Greth, 2018).

Kamyar (2016) derived that a constraining factor for the conventional surface bulk air cooler is that there is a limit to how low the temperatures can drop in the intake shaft as mine personnel uses it for transport and hoisting. The answer for this is the utilisation of a dedicated downcast airshaft that utilises ultra-cold surface bulk cooling. This ultra-cold air achieves safe limits by the time it reaches the bottom of the shaft due to auto-compression and strata heat. It is necessary to be occasionally upgrading the bulk air coolers and refrigeration plant infrastructure.

As mining operations get deeper, the mining depth makes it uneconomical for any surface bulk air cooler to be financially viable. This depth varies between mine sites to mine sites depending on the operating conditions. At the point when the mine achieves this depth, it must utilise underground artificial cooling to keep on relieving the mine's heat load (Mackay, et al., 2010). The primary underground bulk air cooler is commonly placed in the main intake.

This is by far the cheapest and easiest application of refrigeration. Maintenance and supervision are easy and cheaper, and the capital cost of installation is much lower. The heat that is removed from the downcast air is rejected into the atmosphere, which means that the plant is very efficient compared to those that are installed underground. Surface air cooling suffers from the limitation that the air is usually only cooled down to around 3°C, which means that very little cooling is done during the winter and that the best that can be achieved with surface cooling during winter is to provide slightly better than winter conditions in the workings throughout the year (Biffi & Stanton, 2008). Experience has shown that in a deep mine the working places are only about 1°C (wb) cooler during winter than during summer although the mean surface wet bulb temperature is at least 10°C less in winter than in summer. One of the reasons for this is that the colder air picks up more heat from the rock on its long journey through shafts and tunnels on its way to the working faces. Thus, although it is cheaper to cool a given mass of air by 10°C on surface rather than underground, if the net benefit is only to lower the temperature in the working places by 1°C or 2°C, it may be cheaper and equally effective to cool the air right at the working place to a much lesser extent (Sivakugan, et al., 2006).

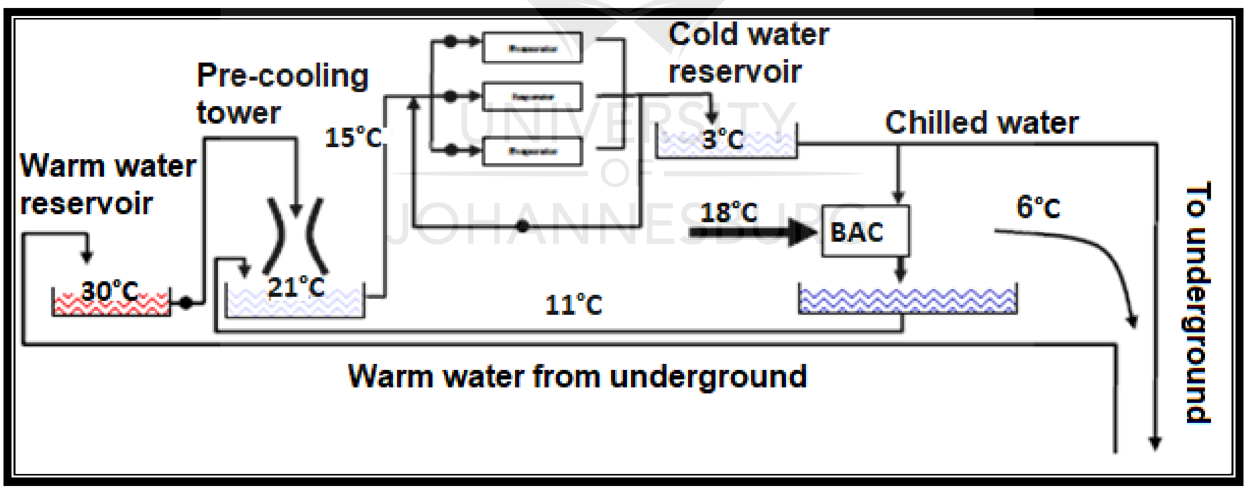

Figure 2-9: A typical surface bulk air cooling layout (Le Roux, 1990).

The following is an explanation of the functions of a bulk air cooler according to (McPherson, 2012):

- Figure 2-9 shows a typical installation where the cooling medium is water;
- Water from underground is pumped to the surface into a warm water reservoir. This reservoir must be of sufficient volume to cater for production peaks and slumps over the mining cycle. Some settling and conditioning of water can be done here if not suitably done in the underground pumping circuit. Evaporators are prone to scaling and corrosion therefore water must be free of excess salts, calcium, carbonates, and sulphides;
- Pre-cooling of the warm water is usually done as it is a cheap cooling method and saves considerably on the costs of running the refrigeration circuit. Any heat re-moved by the pre-cooling is heat that would otherwise have been removed by refrigeration;
- The water is then pumped to the evaporators where heat exchange to evaporator takes place and the water is cooled down, generally to about 3°C. Chilled water is held in a chilled water reservoir, also of suitable design to cater to the production cycle;
- A portion of the chilled water is used in the bulk air cooler to cool down the intake air and the rest is sent down the mine as service water;
- Cooling in the bulk air cooler is generally by direct contact. The intake air is blown through chilled water sprays for heat exchange to take place. In older installations, the air is chilled to around 6°C - 9°C. The latest consideration is "ultra-cooling" – meaning that the air is cooled down to a temperature very close to 0°C. This is achieved by the use of ice as a secondary cooling medium; and
- Bulk air cooler on surface is suitable for shallower operations where the harsh effect of auto compression is not that severe. At depths greater than about 2000m, bulk air cooler on surface alone is not sufficient and secondary cooling becomes necessary. This generally takes the form of bulk air cooler underground, but can also, at greater depths require tertiary cooling, which could be the third stage of bulk air cooler or in-stope cooling using heat exchangers close to the intake of the stoping section or even inside the stope.

2.10.2.2 Underground Bulk Air Cooling

Secondary underground bulk air coolers might be set further in the mine and used to re-cool fresh intake air or re-cool recirculated air. This is known as secondary cooling. Hence, refrigeration plants are regularly placed on the surface (McPherson, 2012). Even though a surface refrigeration plant may provide chilled water, at greater depths, the chilled water may heat up due to the pressure differential. As water is pumped underground the potential energy is converted directly to heat thus warming the water.

A surface refrigeration plant providing cold water to an underground bulk air cooler requires a large system of insulated pipes, pumps, and water dams. There are many drawbacks to operating an underground refrigeration plant. The coefficient of performance is lower as vapor condensing temperatures are increased due to constrained air quantities and the fact that the air utilised for the condenser heat rejection has a higher wet bulb temperature. Underground bulk air coolers can use either an underground or surface refrigeration plant. Underground refrigeration plants perform at higher effectiveness over surface plants as they are nearer to where cooling is required underground. Fouling may be an issue in underground refrigeration plants if the water source is not sourced from the surface because of the substandard nature of underground water. Besides, the maintenance of underground refrigeration plants is difficult because of the bound regions underground (Biffi & Stanton, 2008).

Underground bulk air cooling is done at appropriate points underground, usually close to the point where the air leaves the downcast shaft or at the top of a sub shaft. Although more expensive, the main advantage here is that the seasonal fluctuation of the surface temperatures does not affect the effectiveness of the refrigeration. The underground bulk air cooler is supplied with chilled water, either from surface (if possible) or from a refrigeration plant situated under-ground. The installation of an underground refrigeration plant should only be done as a last resort because of the following limitations (Kamyar, et al., 2016):

- They comprise large equipment units that require large excavations (high cost and stability issues);
- The heat removed from the air must be rejected into the underground air. The deeper the mine, the more problematic this becomes; and
- Maintenance and supervision are not as cheap and easy as with surface installations.

Figure 2-10 shows a typical underground refrigeration layout. Note that the chilled water may also be fed to the bulk air cooler from surface, in which case there would be no underground plant, only insulated pipe columns from surface.

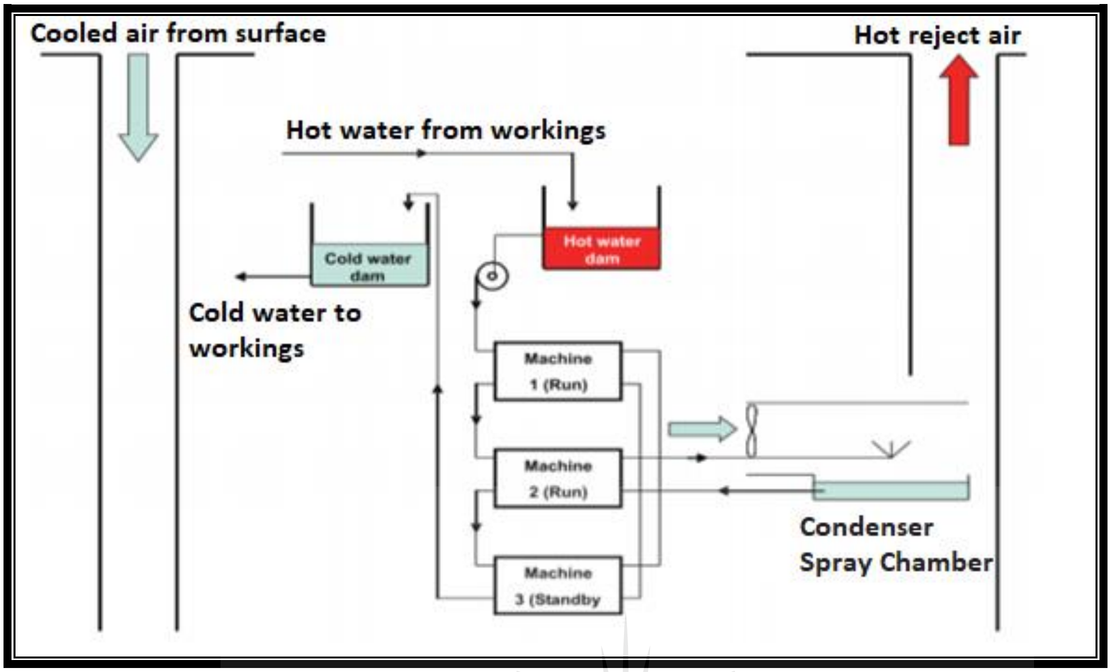

Figure 2-10: Underground refrigeration (Ramsden, et al., 2007).

The following is an explanation of the functions of a bulk air cooler according to (McPherson, 2012):

- Diagram (Figure 2-10) shows a typical installation where the cooling medium is water;
- In this case, there are two separate water circuits;
- The chilled water cycle represents the circuit where water is chilled in the evaporator and then used for heat exchange in the bulk air cooler as well as feed to the chilled service water circuit;
- The cooling water cycle represents the water circuit that cools the refrigerant in the condenser and carries the heat to a cooling tower in the return air of the mine. The return air cools the cooling water by direct spray contact in the cooling tower. The water is collected in a sump, settled, and treated if required, and pumped back into the cooling water cycle;
- The refrigeration circuit located in suitably designed excavations is generally on the main intake level of the mine, close to the shaft. As secondary cooling takes place, the positioning of the downcast air should be re-cooled before it reaches the designed reject temperature;
- The chilled water cycle could also be a closed-circuit cycle. In this case, heat exchange were not direct contact water sprays, but through a heat exchanger that resembles a large radiator through which the air is forced employing mechanical ventilation; and
- Secondary bulk air cooler is generally suitable for depths approaching 4000m. Beyond this depth, the underground heat load becomes so high that the return air does not have sufficient

cooling capacity to make heat rejection possible in a circuit. Under these circumstances, consideration must be given to a split refrigeration circuit where the evaporator is situated underground and the condenser on surface. This is a feasible solution, although fraught with its own unique set of disadvantages. Another alternative to overcome the heat rejection constraints at depth is the use of ice as a cooling medium which was discussed later in this chapter.

2.11 Working Place Cooling

This method involves the cooling of the air very close to the intake to a working place. Figure 2-11 illustrates that chilled water is supplied from a central underground refrigeration plant and distributed to the working places in insulated pipe columns. Cooling is done in smaller heat exchangers that are installed in the individual intake airways of stoping sections. The advantage of this method is that the accelerated heat pick up of colder air is eliminated. This improves the effectiveness of refrigeration (Belle & Biffi, 2018). Disadvantages are:

- Disadvantages associated with underground refrigeration plants;
- The high cost of insulated pipes; and
- The chilled water picks up heat when conveyed over long distances; this reduces the efficiency of the refrigeration and increases cost.

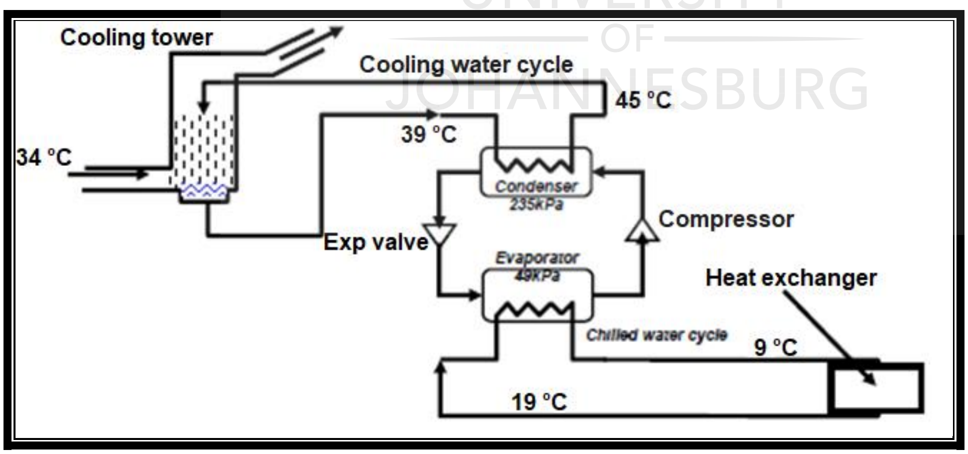

Figure 2-11: A typical layout illustrating working place cooling (Le Roux, 1990).

The following is an explanation of the functions of a bulk air cooler according to (McPherson, 2012):

- The diagram (Figure 2-11) shows a typical installation where the cooling medium is water;
- The circuit shown very closely resembles those of the underground bulk air cooler, with the exception that the chilled water circuit extends to feed chilled water into the workings of the mine. The objective here is to take the chilled water as close to the stope as possible and then use it as a cooling medium to cool down the intake air to the stope (or tunnel). This was done where the heat load was such that the secondary bulk air cooler was insufficient to produce the designed reject temperature in the stope (or tunnel);
- Heat exchange could be by direct contact sprays, but generally uses heat exchangers (radiator type). These can also be installed in the stope;
- Cooling cars in the crosscut;
- In-stope cooling is subject to the same disadvantages as bulk air cooler underground. The added disadvantage is that the chilled water has to be pumped over considerable distances with a resultant "energy loss" along the way. Heat flux into the columns as a result of the temperature differential between the chilled water and the air and the cooling effect is therefore diminished. This is described as a poor positional efficiency; and
- An advantage of in-stope cooling is that only the ventilating air through the stope is being cooled, meaning that a much lower volume is cooled at a lower total refrigeration cost.

2.11.1 Spot Cooling

Spot coolers are smaller, alone standing refrigeration units that may be installed in remotely situated "hot spot" areas. Their main disadvantage is that the heat rejection is done into the return air from the working place. Where this air is already hot, the efficiency is very low, and the desired cooling is not easily achieved. These have not been favoured for some years, but improved technology has made this a more attractive option recently.

Spot cooling systems are frequently alluded to as decentralised, tertiary, face, or in-stope air cooling systems. These spot cooling systems are utilised in areas where heat problems are confined and frequently are far from the main airways (McPherson, 2012). Regularly these restricted areas include actively mined faces as heat is produced from equipment operation and the freshly mined rock/ore. On the off chance that these areas are not active for a significant period, then a mobile spot cooler would be perfect as they can be designed to be portable and thus used in other active production workings. The mobility of spot coolers and their location underground gives them a high positional efficiency (Green & Thorogood, 2018). The disadvantage of a spot cooler is that its size constrains its cooling capacity. Spot cooling systems are frequently utilised in conjunction with central cooling. In any case, if the overall mine heat load is low and localised it might be utilised on its own (Brake, 2001).

The two types of spot coolers which are actively used are:

- Spray chambers; and
- Closed circuit cooling-coil heat exchangers.

An example of a portable spot cooler is shown in Figure 2-12. The evaporator portion of the spot cooler can be installed in an air duct, while the condenser portion is positioned outside of the duct in the return air way where the spot cooler rejects its heat. Another option is to utilise an underground refrigeration plant to provide chilled water to spot coolers. In this circumstance, the refrigeration plant is set up in an area where it can directly reject heat into a return airway. Chilled water is then pumped to where the spot cooler is situated. This can be alluded to as district cooling. Both situations are not constantly perfect, as new airways are not always close to return airways (Brake, 2001).

Figure 2-12: An experimental cooling-coil spot cooler (Greth,2018).

One of the mine secondary coolers used in underground mines is a cooling car. It is positioned underground near to the area where cooling is essential, in this manner allowing mining in areas that would otherwise be out of reach due to high temperatures.

Mine secondary coolers transfer heat from the air stream, through surface or finned tubes, to the process fluid (chilled water). The cooling strategy of the cooling car depends on the conduction and convection heat transfer between the cold water and warm ventilation air (Van den Berg, 2013). Figure 2-13 shows a typical in-line secondary heat exchanger utilised for underground air cooling in mines. Warm air from the surroundings is forced through the coils of a compact heat exchanger (radiator) located inside the cooling car using an electrical fan. As the cold-water flows through the inside of the tubes it is heated, while the air is cooled as it flows over the fin tube assembly of the radiator. The warm water that leaves the cooling car is then discarded into mine trenches, returning it to underground storage dams (Thein, 2007).

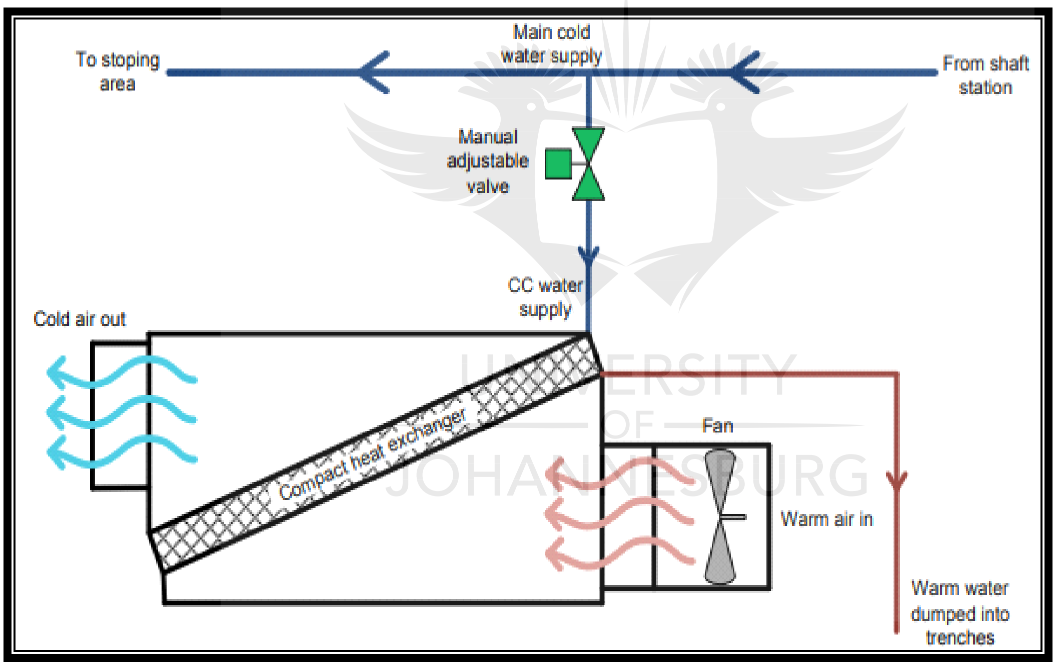

Figure 2-13: Schematic diagram of an in-line secondary heat exchanger used in underground mines (Buys, 2014)

Figure 2-14: In-line type secondary ventilation air cooling car (Buys, 2014)

Figure 2-14 is a typical example of the most commonly used cooling car. The disadvantage of cooling cars is that their size limits their cooling capacity. Cooling cars are frequently used together with central cooling. In the case where, the overall mine heat load is low and localised it might be utilised on its own (Butterworth, et al., 2001).

2.12 Review of In-stope Spot coolers

The air cooler represents a vast improvement over previous technology and has fulfilled the requirements specified by DeepMine for an innovative air cooler, namely that the cooler duty to mass ratio should be increased and that the cooler should be more compact.

Spot coolers have a capacity that ranges between 70kW and 350kW. Heat is normally rejected to the mine service water at temperatures of between 35°C and 45°C. Insulated piping helps to prevent the heat from contacting intake airflows. The service water flow rate varies depending on the temperature but, it is about 0.02l/s per kW of cooling at 21°C water temperature (Calizaya & Marks, 2011).

As elaborated above cooling of air inside the stope is advantageous due to the high positional efficiency (Greth, et al., 2017). The efficiency of a spot cooler can be improved by designing it with a closed loop water cycle to avoid the evaporation of water and increase which leads to humidity downstream from the stope (Oberholzer, 2016).

Under the Deepmine Collaborative Research Programme, Butterworth & Ramsden (2001), together with OEMs, designed three conceptual direct and indirect contact air coolers for conventional mines. The three conceptual air (spot) coolers tested were the finned tube, low pressure indirect contact coil, the high-pressure entrainment cooler for hydropower mining applications, and the direct contact packed fill for low pressure waster applications (Butterworth, et al., 2001).

The parallel-finned tube cooling coil (Figure 2-15), with a weight of 72kg and a length of 1.4m, was made up of parallel finned tubes placed at 30° to the perpendicular. This spot cooler had disadvantages that include the excessive length and anticipated high-water pressure drop and the general coil configuration complexity (Butterworth, et al., 2001). The plate-finned tube cooling coil (Figure 2-16) weighed 70kg and was 0.9m long. It consisted of parallel tubes placed perpendicular to the direction of flow (Butterworth, et al., 2001). The plate-finned cooling coil was complex, and its manufacture would be costly and impractical; the high number of passes and sharp bends would lead to an excessive water pressure drop.

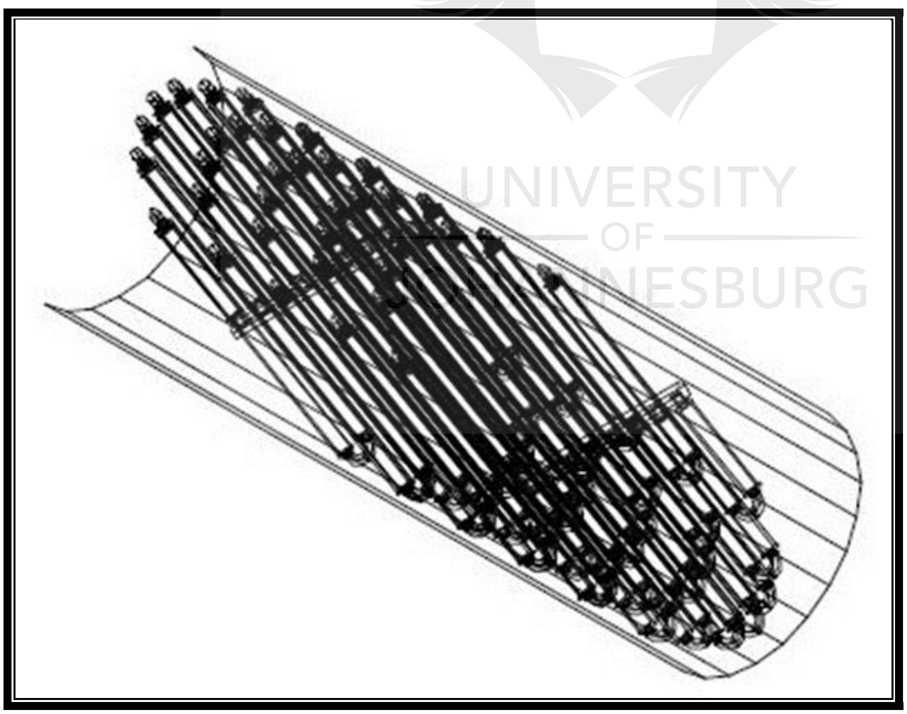

Figure 2-15: Parallel-finned tube cooling coil (Butterworth, et al., 2001)

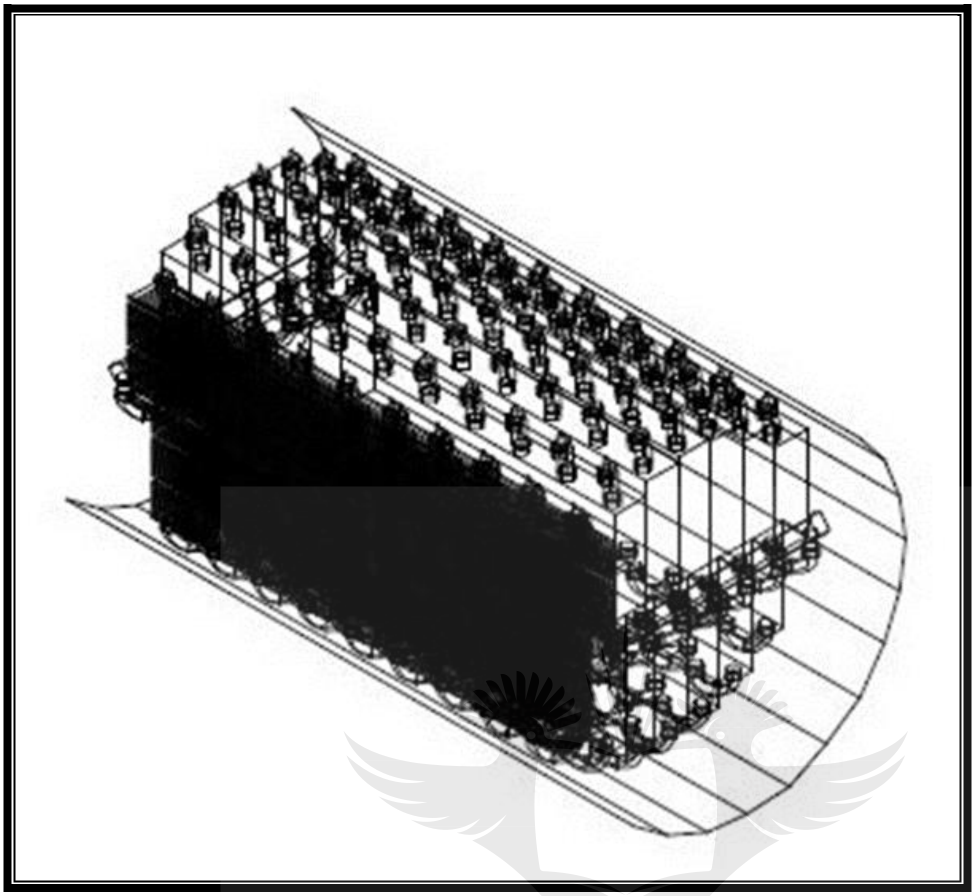

Figure 2-16: Plate-finned tube cooling coil (Butterworth, et al., 2001)

The spiral-finned tube cooling coil (Figure 2-17) was designed to better the coil configuration complexities (Butterworth, et al., 2001). This spot cooler weighed 70 kg, was 0.9 m long, and consisted of a tube that is compatible with standard mining ducts of 570 mm diameter. The tube fins were configured perpendicular to air flow and there was less aluminium welding, limited to eight tubes and two headers. The total net cost of the spiral-finned cooling coil was estimated at R28,100 (2002) (Butterworth, et al., 2001).

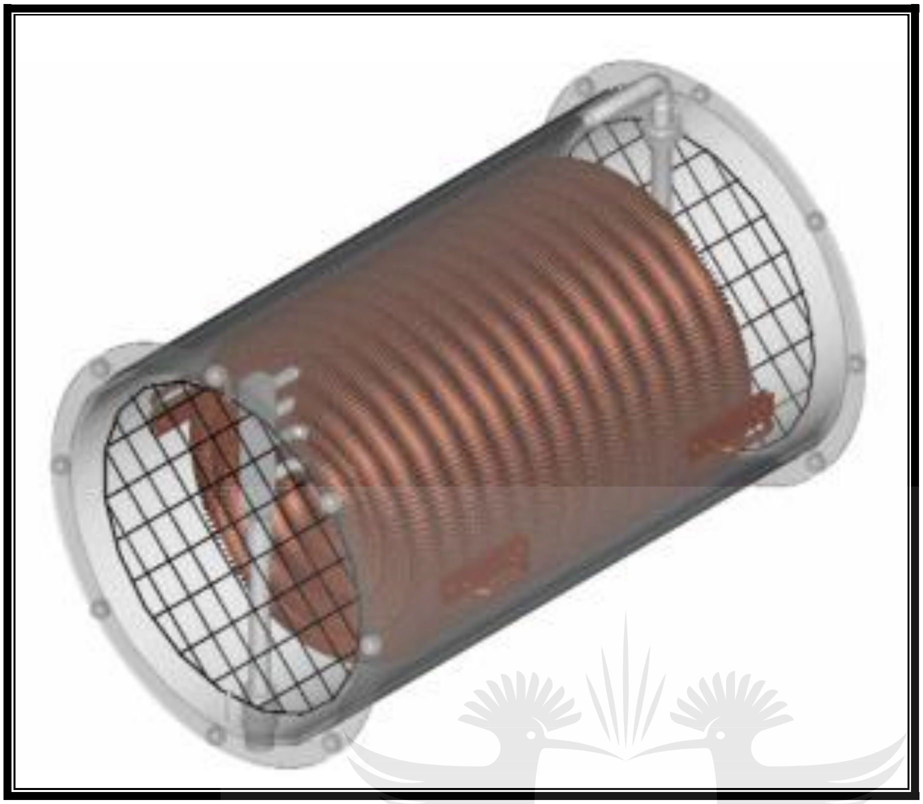

Figure 2-17: Spiral-finned tube cooling coil (Mackay, et al., 2010).

Test results showed that these units performed better than other in-stope spray systems or Venturi cannons, however, the design was not perfected and tested further.

A venturi air cooler (Figure 2-18) exhausts high-pressure water and creates a Venturi effect that entrains air into a ventilation column. Venturi air coolers are used in the stope face and require approximately 18MPa of water pressure at a maximum water flow rate of 0.5l/s. The venturi system entrains about 3m^3/s of air (Du Plessis, et al., 2006).

Figure 2-18: A hydropower Venturi air cooler (Du Plessis, et al., 2006).

The following are some of the recommendations for in-stope cooling based on the Deepmine Project (Butterworth, et al., 2001):

- Water usage should be between 0.8t/t and 1.5t/t (tonne water to tonne rock);
- Chilled stope water should be 12°C for effective cooling;
- The wet bulb temperature of stope intake air should be about 28°C to reduce in-stope cooling requirements;
- Pre-cooling of stope intake air should be conducted close to the stope entrances;
- Water usage in stopes should be controlled; leaks and the discharge of chilled water onto rock surfaces should be avoided;

- In-stope air coolers should be in operation an hour before a shift starts until the end of the shift;
- In-stope coolers should have a nominal duty of 60kW;
- An air velocity of 1m/s should be on the stope face for adequate air cooling power;
- Double brattice curtains should be used in the centre gully to channel enough air to the stope face; and
- In operations that use backfill, intake air should be cooled to 25°C or less so that it does not add to the heat load at the stope.

In climates with seasonal freezing conditions, ice can be created and stored in either a single stope or multiple stopes during colder months and then used during warmer months to cool the mine's intake air. The system also provides heating during winter by raising the intake air temperature due to the formation of ice in the cold stope. Air is forced through the cold stope and either becomes chilled during warmer months or becomes heated during colder months due to heat exchange processes (Greth, et al., 2017).

2.13 Ice as a Cooling Medium

As mining operations become deeper, the depth of 4000m has become a threshold where alternative technology is required to provide effective refrigeration to the underground workings (Van den Berg, 2013). As mentioned before, the rejection of heat is problematic when the heat load of the mine approaches a level that renders the return air incapable of effectively cooling the condenser cooling circuit. In such a case, the use of ice as a cooling medium becomes a very attractive alternative.

2.13.1 Comparison of Ice and Water

Latent Heat of ice is 335kJ/kg and that of a Specific heat of water 4187kJ/kg°C. These properties imply that ice is considerably more effective as a cooling medium than water. One kg of ice provides a cooling effect of 335kJ when it melts. The temperature of one kg of water must be raised by 78°C to provide the same cooling effect. Figure 2-19 is a basic ice flow diagram (Kamyar, et al., 2016).

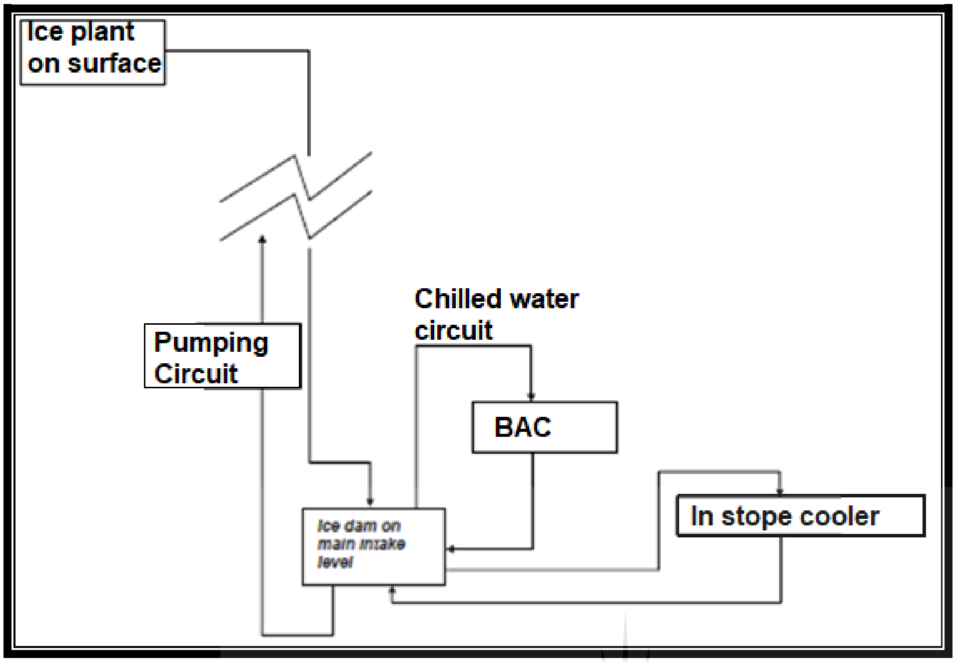

Figure 2-19: Ice flow diagram (McPherson, 2012).

The following is an explanation of the functions of a bulk air cooler (Kamyar, et al., 2016):

- With the use of ice, heat rejection "has already been done on surface". The ice that melts provides the cooling effect to cool the chilled water for heat exchange in the bulk air cooler and/or stope coolers. The return water from the ice dam is still at a comparatively low temperature and does not pose any heat balance dilemmas;
- The volume of ice required is much lower than the volume of water required for the same cooling effect. A mine using ice has claimed that this reduced the volume to 20% of the volume they required when using water. Pumping cost is one of the biggest cost components of the cooling process and a significant reduction in volume pumped have a huge effect on the cost structure of the operation; and
- Disadvantages of ice as a cooling medium are mostly related to difficulties in horizontal and vertical transportation, mainly blockages of columns and freefall damage in vertical columns. None of these are considered to be insurmountable.

2.13.2 Vacuum Ice Process vs Ammonia Ice making

Vacuum-process technology producing chilled water needs no refrigerant of the conventional kind, but water from the process itself is used to generate cooling. This eye-catching novelty incorporates many of the considerations about the future of refrigerants such as ozone friendly, no extra demands for safety measures or for skilful operators, no special requirements concerning the installation's components, and lower maintenance costs since leakages can be accommodated from the system. Vacuum-process technology may be used not only for the production of chilled water (Kühnl-Kinel, 1998).

Liquid ammonia acts as a refrigerant in ice plants. Evaporation of a liquid needs heat energy. When liquid ammonia vaporises, it absorbs large quantities of heat without changing its temperature. For these reasons, ammonia is widely used as a refrigerant. Ammonia can easily be compressed in the form of liquid. Liquid ammonia can easily act as a refrigerant. On the vaporisation of liquid ammonia, it absorbs a large quantity of heat without changing its temperature. This is the reason why ammonia is used for making ice in the factories as it acts as a refrigerant (Tamainot-Telto, et al., 2009).

Vacuum Ice Plant Operation (Figure 2-20):

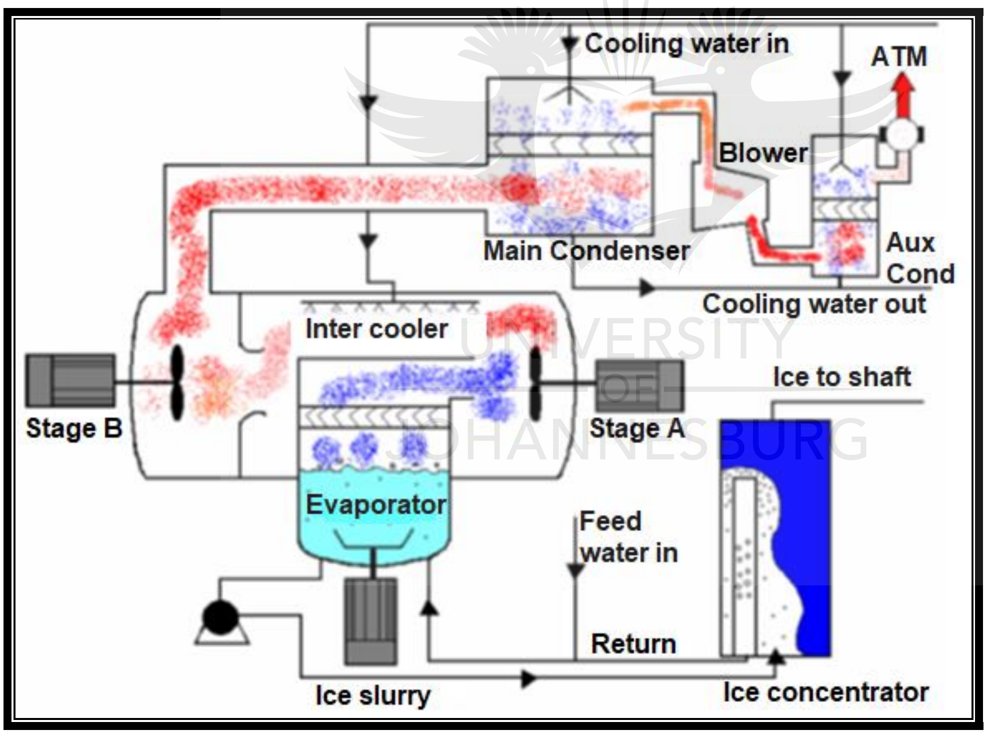

Figure 2-20: Shows a schematic diagram of the 3MW Refrigeration Vacuum ice Plant at AngloGold's Mponeng Mine (McPherson, 2012).

The process uses the phenomenon of the triple point of water, where vapour, liquid, and ice coexist. Inside the VIM (Vacuum Ice Machine), water is subjected to triple point conditions in a tank under a vacuum. The flashing forces part of the water to evaporate while the remaining liquid freezes. Within this process, the latent heat of crystallisation causes evaporation (Van Der Westhuizen, 2000).

- For every kg of vapour flashed off, about 7.5 kg of ice crystals are formed.
- Produces slurry ranging between 17% to 75% ice mass fraction (IMF).

Chilled service water from the fridge plants, at 5°C (wb) is pumped into a freezer vessel that is subjected to vacuum conditions. When water is subjected to a pressure (vacuum) below triple point conditions, a proportion of water flashes off and evaporates. The latent heat required for this evaporation is extracted from the remaining water mass, which consequently becomes partly frozen in the form of an ice slurry.

The ratio of the latent heat of evaporation to crystallisation is about 7.5:1, which is for every kilogram of vapor flashed off, about 7.5 kg of ice crystals are produced. Under controlled conditions, a pumpable ice slurry with an ice concentration of between 16% - 20% is formed within the freezer vessel. The ice is kept in dynamic suspension by an agitator, which is constantly renewing the water surface, whilst the minimum salinity in the vessel prevents the ice crystals from coalescing to form large ice chunks in the vessel (Kühnl-Kinel, 1998).

The water vapour that is drawn off is compressed by two unique compressors operating in series and delivered to the direct contact condenser where it condenses on the counter-flow cooling water from the condenser cooling towers. The compressor is designed to compress high volumetric flow rates over a high compression ratio (1:8 across the two stages). At the low pressure in the evaporator, the water vapour has a very low density and resultantly a high specific volume. The mass flow rate of water vapour is around 12% of that of the slurry and represents a large volumetric flow rate (320m^3/ sec) (Tamainot-Telto, et al., 2009).

An extraction system collects the Non Condensable Gases (NCG) after the condensers and removes them from the system via a positive displacement blower, auxiliary direct contact condenser, and vacuum pumps. The heat generated in the process is rejected via cooling condenser water, the condenser cooling tower operating as the 'heat sink' for the system.

A slurry pump, rated to deliver approximately 200m^3/hour, is used to pump out the brine slurry with 16% - 20% ice by volume from the unit to the ice concentrator, where the slurry is concentrated to an Ice Mass Fraction (IMF) of 75%. The brine solution, drained from this slurry, returns from the concentrator back to the freezer via the buffer tank. The ice concentrator is in effect a hydraulic piston where the ice cake rises on top of the brine solution and is concentrated, whilst the brine solution drains off and is returned to the freezer (Van Der Westhuizen, 2000).

The ice is harvested off the top of the concentrator by a scraper, dropped into a rotary valve, and pneumatically transported to the shaft where it is then sent underground.

Ammonia ice plant operation (Figure 2-21):

- Ammonia is used to cool down;
- Ammonia is used to chill water on plates to form ice;
- Gassed off ammonia is used to heat the plates to dislodge the ice; and
- Ice falls on the screw feeder and is conveyed to the shaft.

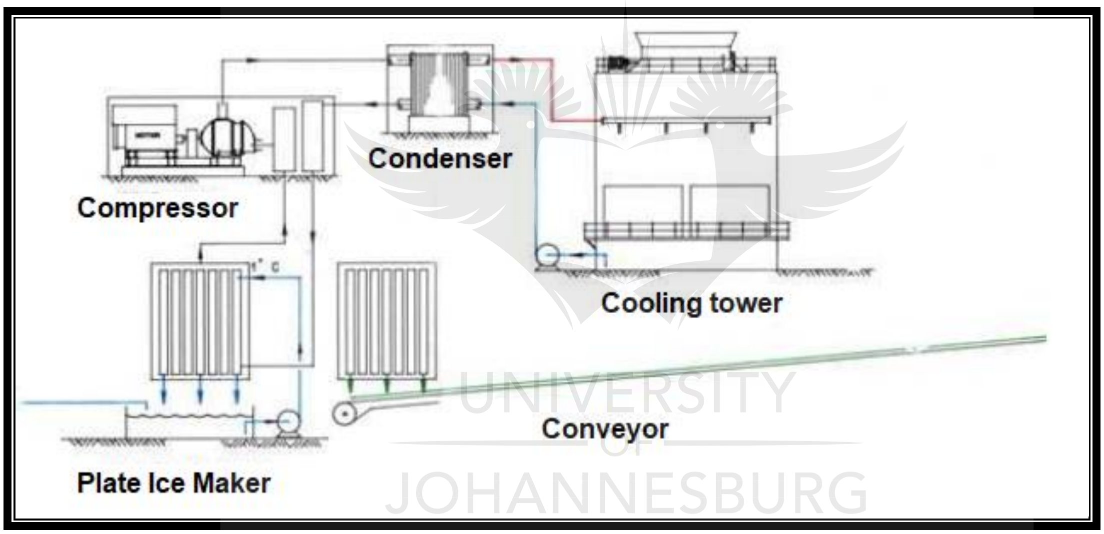

Figure 2-21: Schematic Diagram of Vacuum Ice Process (McPherson, 2012).

Table 2-5 displays the comparison of vacuum and ammonia ice plant operations by McPherson (2012) where the ammonia ice plant is cheaper and operates with proven technology. Ammonia is also regarded as harmful to people but could be managed safely during use. On the other hand, the vacuum ice plant is more costly at R7000/kW and its technology is still being developed. Unlike the ammonia ice plant, the vacuum ice plant uses water that is not harmful however, the brine solution tends to mess up the environment.

Table 2-5: Comparison of Vacuum and Ammonia Ice Plant Operation

	Vacuum	**Ammonia**
Cost	R7000/kW	R5200/kW
Ice mass fraction	70%	90%
Ice: Water ratio	3.8 x less pumping	5 x less pumping
Technology	Still developing (Compressors surging due to high ambient temperature)	Proven (ERPM)
Efficiency	High 242 tonnes / MW	11MW=9MW nominal 312 tonnes / MW @ 70%IMF
Safety	Water not harmful	Ammonia harmful to people
Environment	Salt / Brine mess up environment	Ammonia not harmful to nature
Risk	Salt damage Steelwork	Ammonia could be managed safely

(Van Der Westhuizen, 2000).

A few steps that outline ammonia safety for the people and what to do when exposed to ammonia are briefly described below according to the New York department of health (Centers for Disease Control and Prevention and others, 2004).

<u>Ammonia Safety (People):</u>

Inhalation: Ammonia is irritating and corrosive. Exposure to high concentrations of ammonia in the air causes immediate burning of the nose, throat, and respiratory tract. This can cause bronchiolar and alveolar edema, and airway destruction resulting in respiratory distress or failure. Inhalation of lower concentrations can cause coughing, and nose and throat irritation.

Skin or eye contact: Exposure to low concentrations of ammonia in air or solution may produce rapid skin or eye irritation. Higher concentrations of ammonia cause severe injury and burns. Contact with concentrated ammonia solutions may cause corrosive injury including skin burns, permanent eye damage, or blindness. The full extent of eye injury may not be apparent for up to a week after the exposure. Contact with liquefied ammonia could also cause frostbite injury.

Ingestion: Exposure to high concentrations of ammonia from swallowing ammonia solution results in corrosive damage to the mouth, throat, and stomach. Ingestion of ammonia does not normally result in systemic poisoning.

<u>What to do if exposed to ammonia:</u>

In the case of an accident, people are to be led out of the contaminated zone. Give oxygen if available and wash with plain or saline water for more than 5-minutes if there had been skin contact.

There is no antidote for ammonia poisoning, but ammonia's effects can be treated, and most people recover. Immediate decontamination of skin and eyes with copious amounts of water is very important. Treatment consists of supportive measures and can include administration of humidified oxygen, bronchodilators, and airway management. Ingested ammonia is diluted with milk or water.

<u>Ammonia Safety (System):</u>

For safety reasons, it is important to always wear gloves and safety glasses when handling apparatus related to ammonia. At the ice plants spray showers over plate heat exchangers, compressor seals, and pressure relief valves are made available. It is advised that building ventilation be done with louvers and extraction fans. Water spray scrubbing installed in the draught area of the fans allows a quick wash in case of an accident. Ammonia detection sensors in the building increase awareness. Fire extinguishers at each door, fire reel, and hose installations make sufficient water available. Lastly, a breathing apparatus at each door minimise exposure to ammonia from inhalation.

2.14 Ventilation Air Leakages

Multilevel mines with involved ventilation patterns, large stoped areas, and numerous bulkheads are often subject to serious air leakages that are difficult to track down, in this case, a tracer gas can be used. The Bureau of Mines successfully employed sulfur hexafluoride (SF_6) to measure and identify ventilation problems such as air leakage through old stopes, doors, and cracks. The simplicity and accuracy of the tracer gas technique in studying ventilation systems where conventional methods fail warrants serious consideration of adopting the tracer gas as a standard ventilation tool (Thimons & Kissell, 1974). The assumption would be that air leakages will be managed because if 100% of the air is being cooled and 50% is leaking, that will still be wastage. Even with cooling cars, the reality is that they are not that effective because of the damage to the unit caused by the environment underground.

Some of the control measures to handle leakages are to coat high pressure face of the stoping, crossing airways, maintaining a neutral pressure underground, and using multiple fans (McPherson, 1964):

- Coat high pressure face of the stopping with a sealant material and particular attention paid to the perimeter;
- Use air crossing where intake and return airways are required to cross over each other then leakage between the two must be controlled;
- Maintaining a neutral pressure underground minimises the degrees of air leakage between the workings and the surface; and
- Use of multiple main fans offers the potential for improved distribution of airflow, air pressures, and leakages, etc.

2.15 Micro-climate Cooling System

Micro-climate cooling system is used to provide personal cooling and heat stress mitigation to individuals subjected to elevated ambient temperatures or wearing thermally restrictive clothing. Laboratory evaluations have demonstrated that microclimate cooling systems effectively reduce the thermal strain induced by the combination of work, clothing, and environment. With the use of these garments work times can be increased and physiological strain, as measured by core temperature and heart rate, can be decreased. Microclimate cooling system appears to have their limitation, however, with the combined effects of high temperature, moderately heavy workloads, and heavily insulated garments, such as the PPE (personal protective equipment), the current cooling garments can become overburdened and, under these conditions, their ability to reduce physiological strain is still considered somewhat limited (Janik, et al., 1988).

Micro-climate cooling is the cooling of the area directly surrounding the mine worker. This is ideally the most efficient way to keep the mine workers cool in a hot underground mine environment as the positional efficiency can be close to 100%. The above mentioned methods have with them other challenges, such as large initial investment, high operating cost, noise pollution, poor cooling effect, difficulty in moving and installing refrigeration equipment, potential safety hazards, and so on. (Brake, 2001).

Several mines are experiencing high temperatures worldwide especially in South Africa as the mines go deeper and work further from the shafts. Under such conditions, conventional ways of controlling the climatic environment can be inapplicable and/or uneconomic. One of the ways of obtaining the appropriate level of climatic control, to ensure worker health and safety as good production is still attained is to adopt a method of active man cooling (Tuck, 1999). This method can simply be considered as the reverse of the normal cooling techniques mentioned above, where the cooling power of the ventilating air is enhanced.

This method is not often mentioned in underground mine cooling literature as micro-climate cooling systems do not cool the mine environment. Nevertheless, an example of this is utilising the following garments.

2.15.1 Cooling Garments

In hot mining conditions, it is important to assist the body's thermoregulation framework with an artificial cooling technique. These cooling garments can be ordered into two classifications: passive and active garments. Passive garments do not include any mechanical or electrical equipment to operate and can be separated into two known sorts: the phase-change garment, or PCG, and vacuum desiccant cooling. The outstanding sorts of active garments are air-cooled garments or ACG, liquid-cooled garments (LCG), cooling garments dependent on gas development, and hybrid cooling garments.

<u>Air-Cooled Garment (ACG)</u>

In air cooled garments, compressed air is supplied from an external air supply system. This garment contains two layers of which the external layer is impermeable to the encompassing air, and the second is air-permeable and in direct contact with the skin. Air is blown between the two layers and leaves the garment through the internal layer towards the skin (Al Sayed, et al., 2016). ACG's essential method of cooling is by dissipating the body's perspiration. In any case, the effectiveness of air-cooled garments in situations with high moistness levels is extremely constrained. The garment's execution results show low effectiveness in lessening the body's thermal physiological reactions, yet they expressed that the garment could be utilised, after practicing in gentle warmth, to enhance thermal solace and decrease warm pressure (Hadid, et al., 2008).

In comparison to the liquid cooled garment described below Sarkar and Kothari (2014) advocate that air-cooled garments have advantages such as:

- It is a positive pressure system, a small leak or tear in the garment is less likely to contribute to contamination of the wearer; and
- It is easier to manipulate than a liquid cooling system as it is simple to connect and disconnect.

The above two researchers further explained the major disadvantages of this cooling garment:

- Cooling efficiency is inferior most probably as a result of low heat capacity of the air; and
- The ACG is non-profitable. They are found to be inadequate in applications like space, hot industries like the mine.

<u>Liquid-Cooled Garment (LCG)</u>

The failure of ACGs to provide the desired effective cooling leads to the development and invention of liquid cooled garments. These garments are the most commonly used. In comparison to air, the higher heat capacity of water provides engineering advantages with the likes of reduced pumping power, lesser weight, and lesser bulk (Sarkar & Kothari, 2014).

Liquid-cooled garments (LCGs) utilise a cooled liquid (for the most part water) that circles, inside cylinders inserted in the garment, utilising a micro-pump controlled by a battery. These tubes are typically made of polyvinyl chloride (PVC). Numerous investigations directed on subjects wearing LCGs demonstrate that these garments can enhance performance (work duration) and decrease thermal strain. The cooling efficiency of liquid cooling garments depends on environmental conditions, the types of tubes used (length too) and flow rate, etc. Eternal heat can also get to the tubings or can indirectly be taken in by the garment itself. Humidity plays an important role in controlling the cooling (Sarkar & Kothari, 2014).

The negative aspects of LCGs are that in a humid environment if the water circulates in the space between the skin and the personal protective equipment, steam may appear and cause skin burns. When the ambient air temperature is higher than the liquid coolant as is the case in deep mines, the coolant can gain heat from the environment resulting in a heat transfer that will reduce its cooling efficiency (Al Sayed, et al., 2016).

The diagram above Figure 2-22 shows the comfort zone for water cooled garments. Each heat load has a range of skin temperature which interacts with human thermoregulation and minimises sweat secretion. Heat discomfort is defined by heat storage and sweating. Cold discomfort means shivering. The dashed line indicates the lower limit of active sweating.

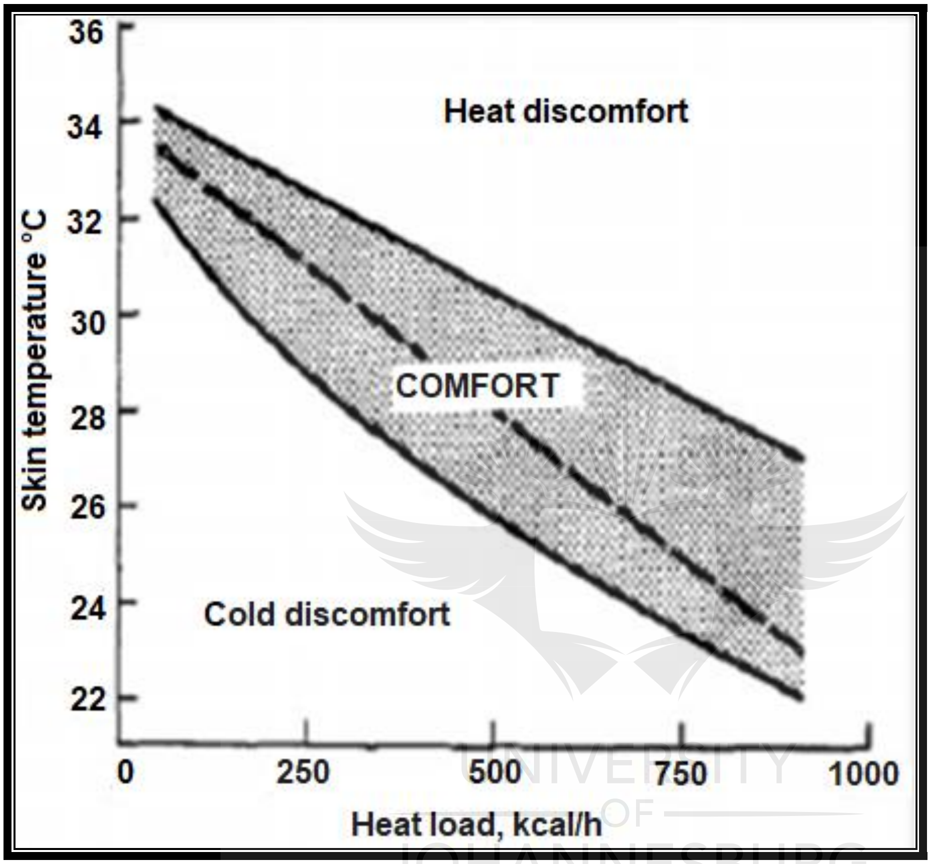

Figure 2-22: The comfort zone for cooled garments (Al Sayed, et al., 2016).

Nunneley (1970) concludes that water cooled garments can provide a high level of wearer comfort as compared to ACGs, besides, liquid cooled garments have good compatibility with other protective garments. However, LCGs are known to be expensive and need a very close fit to the wearer. The concerning safety problems include spillage that could result in short circuits, steam burns and the uncomfortable sensation on the skin from the wet clothing.

Cooling Garment Based on Gas Expansion

This kind of cooling garment does not need power to work and depends on the endothermic vaporisation of condensed carbon dioxide (CO_2). High-pressure CO_2 is dispensed through an expansion valve in which the gas pressure drops to the ambient value. In this thermodynamic evolution, fluid CO_2 flashes to vapour and assimilates energy equivalent to the gas' heat of vaporisation (Al Sayed, et al., 2016).

Phase Change Garment (PCG)

The phase-change garment utilises materials that can assimilate and store thermal energy in latent heat form at a temperature range reasonable for individual cooling purposes. As a rule, a PCG covers the torso and contains pockets encompassing the chest cavity that holds the phase changing material packs (C de Klerk., 2001).

Phase change cooling garments generally use dry ice or ice as the coolant. Body core-skin temperature gradient is formed due to the cooling effect of ice or dry ice by latent heat of melting and latent heat of sublimation. Body cooling thus takes place mainly by conduction. For the use of any phase change material in cooling garments, it is very important to know the enthalpy in the working zone since the amount of thermal energy that can be stored depends on the enthalpy variation around the phase change. (Sarkar & Kothari, 2014).

Based on the materials used, phase change cooling garments can also be classified into two major categories, these are inorganic compounds and organic compounds. Inorganic phase change materials can be salt hydrates, salts, metals, and their alloys, whereas organic phase change materials can be paraffin waxes (or n-alkanes), polyethylene glycols, and fatty acids.

Cooling Garment Based on Vacuum Desiccant Cooling

A prototype of a cooling garment in light of vacuum desiccant cooling was tried at 40°C and 50% relative heat atmospheric conditions by 2012 (Chan, et al., 2015). The cooling garment had contained the following - a cooling core containing water, an absorption core, a honeycomb-type spacer, and an outer bag made of plastic. The prototype weighed approximately 3.4 kg and covered $0.4m^2$ of the body surface. Chan *et al.* (2015) determined that this prototype has a maximum cooling capacity of $373W/m^2$ and concluded, that this prototype is more successful than an ice-cooling vest at diminishing the core body temperature and heat stress while the wearer is working in a hot environment (Butterworth, et al., 2001).

Thermoelectric Cooling

Thermoelectric gadgets utilised in thermoelectric cooling depend on the Peltier Effect (a temperature difference created by applying a voltage between two electrodes connected to a sample of semiconductor material) to convert electrical energy into a temperature gradient. A thermoelectric module offers numerous preferences: its size, high dependability, no vibrating parts, and direct vitality change. Their principle shortcoming is the poor coefficient of performance, especially in large capacity and wide temperature range applications (Al Sayed, et al., 2016).

Hybrid Cooling Garments

Hybrid cooling garments join at least two cooling techniques in one functional system. The most notable sort is the air-liquid cooling garment used by the National Aeronautics and Space Administration (NASA) for extravehicular activities in space. It contains flexible spandex, vinyl tubes through which a coolant circulates, and an airflow duct, which is stitched over the garment that mostly cools the head (Ando, et al., 2015).

In conclusion, the air-cooled garment is viewed as a light-weight garment that keeps clothing drier and relies on the body's mechanism (sweat) to dissipate heat thus disposing of the danger of overcooling that could happen with different types of garments. At elevated amounts of heat, the effectiveness of the air-cooled garment diminishes, because the surrounding air is saturated (Barwood, et al., 2009).

As of now, no cooling innovation appears to meet the full requirements for deep underground environments. A cooling garment should be light, compatible with the work of miners, present no risk to health and safety, and significantly reduce heat stress. Consequently, further examinations and studies on different combinations of cooling technologies must be led to achieve an ideal cooling garment that is adjusted for miners in deep mines (Al Sayed, et al., 2016).

DeepMine (Marx & Franz, 1999) conducted research to distinguish and assess practical body-cooling garments for deep-level mining applications. The exposure of workers to raised environmental temperatures cannot generally be stayed away from as expelling all or part of the excessive heat from the workplace by using engineering controls is sometimes either impractical or impossible. A few kinds of body-cooling garments have been created to date. In general, the principle of operation is to provide a cool micro-environment around the wearer to facilitate the expulsion of metabolic heat from the body and to block heat exchange with the outer environment, thereby controlling the wearer's heat stress. The type of cooling garment utilised depends almost entirely on the nature of the task at hand and the expected thermal conditions. Monetarily accessible body-cooling systems go from complex circulating air or liquid cooling systems to simpler methodologies such as the utilisation of ice vests.

2.15.2 Recent Work

Zhai (2017) carried out some research work on the vortex tube type of mine cooling jacket that uses a vortex tube refrigeration principle. Zhai describes this jacket as designed to use compressed exhaust gas, which could solve the expense of using electricity by large-scale cooling equipment, according to its design the jacket may not emit toxic gases during its function. Figure 2-23 shows the air flow of a vortex tube.

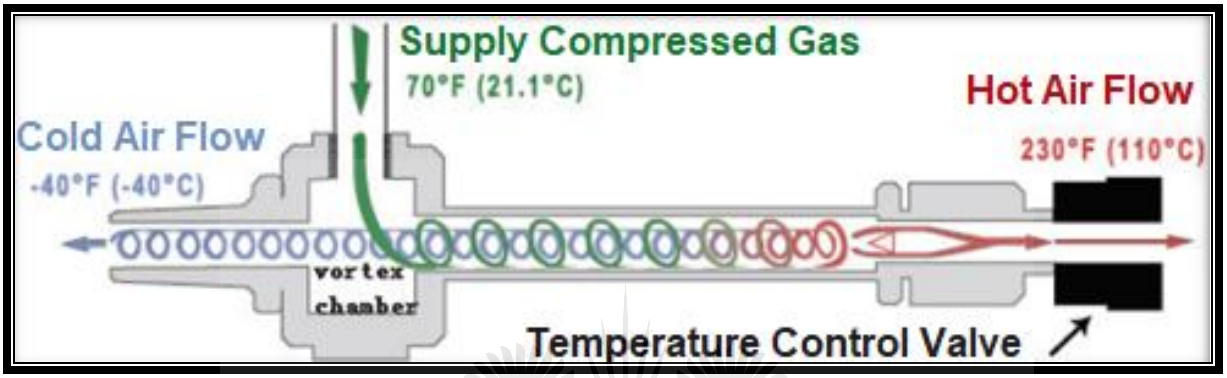

Figure 2-23: Schematic diagram of air flow in a vortex tube (Zhai, 2017).

Figure 2-23 illustrates how the jacket passes cold air through the hole in the vest, the air then travels to the user's back, chest and face, so that the user's torso is kept in a comfortable temperature. This allows employees to maintain a high working efficiency thereby enhancing their safety in the hot environment.

The vortex tube is a new type of energy separation equipment, which consists of the nozzle, vortex chamber, orifice plate for separation, hot-side control valve, and hot-end tube. During the operation of the vortex tube, the high-pressure gas enters the vortex chamber along the tangential direction of the inlet, and a high speed rotational movement of the gas generates eddy current effect in the swirl chamber, which is separated into two parts of the air with different temperature. The cold air in the central part flows through the orifice plate for separation and is output from the cold end tube to the inner layer of the cooling jacket. At the same time, the hot air of the outer part flows out from the hot-end tube through the hot-side control valve (Zhai, 2017).

The manual knob and thermometer it carries can be switched on or off immediately hence it is easy to control and adjust the outlet temperature of the air conditioner. If the pressure and temperature at the inlet of compressed air are constant, the vortex tube outlet temperature will also remain constant within the range of plus or minus 0.6°C which provides 5°C - 20°C constant temperature environment to the wearers' torso (Zhai, 2017).

Its portability, coupled with its low cost allows for a wide application prospect in the underground operation, especially the fixed operation point. Compared with various types of refrigeration cooling jackets, the vortex tube type of mine cooling jacket has the advantages of being stable, reliable, energy-saving, environmental protection and safe performance, convenient installation, and disassembly, easy to maintain, and so on. It also can be used in a harsh environment. These above-mentioned benefits are suitable for underground operation.

Another personal cooling garment was developed for use in deep mining activities as shown in Figure 2-24. The garment weighs 5.1 kg and uses the atmospheric discharge of highly pressurised CO_2 (liquid CO_2) to create a cool microclimate with an average temperature of 12.5 (±0.4) °C between the body (torso) and its surrounding environment (Al Sayed, et al., 2016).

Figure 2-24: Front view, back view, and the air treatment system of the cooling garment (Al Sayed, et al., 2016)

The garment's cooling efficiency was evaluated, in an experimental procedure that was participated by 19 males. Two modes, cooling on and off, were compared. Significant physiological differences were found between the two modes after minute 27 until the end of the recovery phase for the heart rate (maximum difference of 10 beats per minute) and the internal body temperature (maximum difference of 0.33°C) (Al Sayed, et al., 2016).

The results of this experiment show that the cooling garment lowered the subjects' internal body temperature and heart rate. The garment (Figure 2-24) also effectively improved the subjects' well-being, thermal comfort, exertion level, and reduced the humidity sensation (Al Sayed, et al., 2016). These findings provide strong evidence of the cooling garment's ability to reduce heat stress in an environment simulating the work conditions of deep mines (Al Sayed, et al., 2016).

This study has shown limitations when compared to an actual mining environment. The average age and body weight of miners are higher than those of the subjects that participated in this study (Ngô, et al., 2017). Another limitation is that the workload and surrounding conditions (temperature and relative humidity) also vary from the conditions simulated in this study. However, future studies must direct their efforts and resources towards testing the garment's effects with real miners in real mining conditions as they are the ones who will be using these jackets (Al Sayed, et al., 2016).

2.15.3 Comparative System Analysis

The comparison of mine cooling systems is often tough, this is because there are not only various cooling systems, but each system varies by cooling capacity, operating cost, capital investment, efficiency, and more. The efficiency of these systems varies between different mine sites based on a variety of factors such as mine design, mining method, material handling, heat load, and more. Table 2-6 highlights the advantages and disadvantages of current cooling system strategies. It shows that each cooling system delivers an exclusive set of capabilities that can be implemented by a mine to decrease its heat load. Though a single system may be able to reduce the heat load to appropriate levels, a cooling system strategy is often developed based on multiple systems. As the mine continues to deepen and becomes increasingly mechanised, more cooling is implemented by upgrading the current cooling infrastructure and/or by implementing more or other cooling systems.

Most often, surface bulk air cooling is utilised solely or first when implementing cooling due to its large cooling capacity, ease of maintenance, and lower installation costs relative to underground cooling infrastructure (Van den Berg, 2013). This is only the situation when the mine design permits for the chilled air to be directly moved to specific areas underground experiencing excess heat. Other cooling methods would need to be employed if the chilled air from the surface bulk air cooler system is unable to reach these regions or the mining depth and associated geothermic gradient is too large for a surface bulk air cooler system to be efficient (Brake, 2001).

Table 2-6: Cooling Systems-advantages and disadvantages.

Cooling System	Advantages	Disadvantages
Surface Bulk Cooling	Provides the greatest amount of cooling	Limited by the depth of the mine
Underground Bulk Cooling	Generates the largest amount of cooling capable underground	Must reject heat to a return airway or through return waterlines to the surface
Ice Storage	Utilises natural cooling processes to reduce operating costs	Limited to cold climates
Spot	Mitigates heat in localised areas	Must reject heat to a return airway or through return waterlines to the surface
Micro-Climate	Cools area directly around the mine worker	Workers are unable to always remain in air-conditioned cabs Current cooling garments are not optimal for use in the mine environment

(Greth, 2018)

2.16 Mine Cooling Efficiency

Many things can be done to improve air flow in the mine. Ventilation engineers must enquire, measure, and thoroughly understand the mine airflows and quality of underground mine (Pritchard, 2010).

The overall effect on mine cooling efficiency takes in two forms: first by the loss of refrigeration or increased chill in the water temperature arriving in a given section and second, by a loss in transfer efficiency when the gap between the arriving water temperature and the actual air temperature decreases.

The quality of underground insulation systems outside the general refrigeration plant areas is poor. The non-insulation of flanges coupled with the poor maintenance of damaged sections add to the low overall efficiency of the chilled water reticulation systems.

The loss of efficiency of mine air cooling devices such as stope cooling cars (fin and tube), in-stope coolers can be even higher when fins and tubes are fouled (Rawlins, 2007). Additionally, 40% of ventilation air goes into old areas or where not needed.

2.17 Republic of South Africa

The DeepMine Research Programme (Schutte & Franz, 2000) examined the thermal environment conditions at the scene of reportable accidents for every single gold mine supporting the conclusion of the literature that heat stress affects both safety and productivity. The research outcomes indicating that elevated thermal conditions (>29,0°C (wb)) harmfully impact injury and production rates and 32,5ºC (wb) as the limit for routine work. According to the law of minimum velocities, Harmony uses 0.4m/s (Department of Mineral Resources, 2002).

Current South African legislation necessitates that no person shall work in a mine where the conditions are conducive to heat stroke, except if such work is carried out in harmony with an approved code of practice. In terms of a conservative but practical limit, thermal conditions 'conducive to heat stroke' exist, albeit only potentially so, whenever the wet-bulb temperature equals or exceeds 27, 5°C (wb) (Schutte, et al., 1994). The research also concluded that the thermal environment would influence a worker's capacity to perform and coordinate movements in constrained space with speed and precision. Once the wet-bulb temperature rises above 29°C, individuals work quicker but less precise than they would beneath this temperature.

According to SIMRAC research (Schutte, et al., 1994), the Emergency Heat Stress Index (EHSI) recommended action levels are:

- EHSI ≥28°C: emergency work to be undertaken only by heat tolerant or heat acclimatised task forces, no time limits but work should proceed under supervision and with regular water breaks;
- EHSI ≥30°C: special precautions and tolerance times to be observed; and
- EHSI ≥45°C: maximum permissible upper limit, no work should be undertaken unless whole body cooling is feasible.

Basing on the terms of the DMR legislation, it describes that If the temperature exceeds 27,4°C (wb) or 37°C dry bulb or 37°C globe temperature (an indication of radiant heat) at that point a mine must begin to implement heat stress management (Schutte, 2018).

2.18 Australia

In their article Belle & Biffi (2018) advocate that mines in Australia need to manage high ambient temperatures and humidity, owed to the very steep virgin rock temperature gradients in the operational and planning phases (Bluhm & Smit, 2004).

In Australia, Mount Isa Mines have grounded their heat stress limits on wet-bulb temperatures incorporating air velocity measurements. They have presented the "short shift" protocol which decreases the working shift length to six hours where workers have worked in thermally stressful conditions that are greater than 31.5°C (wb) temperatures for more than two hours. Once a wet-bulb temperature above 32.5°C is reached the job is stopped (Kocsis, 2009).

Additionally, the Enterprise Mine at Mount Isa is anticipated to reach a depth of almost 2000m underneath the surface. Brake (2002) simplifies that the effects of high surface ambient temperatures in summer, together with auto compression in the intake airways and high virgin rock temperature results in heat stress in the working place that, without intervention, would surpass the levels that human physiology can endure. Refrigeration, utilising surface bulk air cooling, underground air cooling, and chilled service water, will play a major part in providing a suitable working environment. This is in contrast with the technique of "flooding" the mine with air to eliminate heat, which is employed at the other Mount Isa underground mines. On the other hand, it is unavoidable to consider the costs that come with the implementation of the possible examples of cooling that Brake suggests.

Anglo Gold Ashanti's Sunrise Dam operation situated in Western Australia, explores numerous ventilation scenarios which include upgrading the present fan stations, rentals, establishing a common ventilation backbone, and establishing new upcast infrastructure for the district to sustain the short-term production increase. Nevertheless, in considering the likely long-term ventilation necessities, it becomes apparent that Sunrise Dam requires significant upgrades in the future.

The following regulations relate to ventilation and temperature limits and requirements for underground environmental control in Australian mines (New South Wales Government, 2014):

2.18.1 Regulation 9.14.1, Air Underground Workplaces

The manager of an underground mine must ensure that ventilation air provided for the mine is of adequate volume, velocity, and quality.

2.18.2 Air Temperature

Each responsible individual at a mine must cause all necessary measures and precautions to be taken to guarantee that employees do not suffer harm to their health from the adverse effects of extremes of heat or cold.

If conditions in the work environment are or are probably going to be hot and humid, each responsible person at the mine must guarantee that:

- All workers are provided with training in measures to be taken to evade harmful effects from those conditions; and
- Suitable workplace environmental controls (including ventilation) and monitoring are implemented, and If suitable, a programme for monitoring the health of employees in the workplace is executed.

In any workplace in an underground mine, and any tunnel under a surge stockpile on the surface of a mine, the manager of the mine must safeguard that: if the wet bulb temperature surpasses 25°C, an air velocity of not less than 0,5m/s is provided (New South Wales Government, 2014).

2.18.3 Ventilation Regulation 4.13, Hot Conditions Underground (State of Victoria)

The Australian State of Victoria's requirements for thermal limits in underground workplaces states that when the underground temperature of the air in a place where an individual is required to work or enter exceeds 28°C (wb), the manager must take precautionary measures to prevent, as far as practicable, the risk of heat stress related injuries or outcomes.

In Australia, certain activities are prescribed for various levels of air-cooling power. In considering the tabulated values, it must be valued that levels of mechanisation in Australian mines are considerably more advanced than in South Africa and that the Australians make extensive use of air-conditioned cabins for equipment operators.

2.19 Canada

Different regions and provinces use different regulations and standards which were implemented by the Canadian Standards Association (CSA) (Halim, 2017).

Worldwide, metal mines are going deeper. For instance, in Canada, six mechanised metal mines are planning the extraction of ore reserves at 3000m depth. Working at such depth tests all aspects of mining technically and economically, including the distribution of fresh air to the production areas. Concerning Canadian metal mines, three general trends can be observed (Hardcastle & Butler, 2008):

- Mines are getting deeper;
- Mining operations are becoming progressively mechanised;
- Health and environment standards for underground employees are becoming harsher; and
- To varying degrees, these detected trends coupled with increasing energy costs continue to challenge the economic sustainability of the mines, as well as the economic provision of ventilation in large and deep metal mines (Kocsis, 2009).

2.19.1 Mechanical Ventilation

Each underground working must be mechanically ventilated with a system that:

- Designed, installed, and operated, and maintained in good working conditions according to best engineering practice; and
- Supplies enough air to the underground workings (Stinnette, 2013).

2.19.2 Air flow

"The main ventilation system must be capable of functioning on blowing or exhaust duty and be equipped with a reversing switch, which typically will operate on exhaust, and the air flow must be" (Stinnette, 2013):

- At least 15m^3/min for each square meter of the working face;
- Where internal combustion engines are used, the total air flow should be as specified on the engine permits;
- If ventilation systems fail, working must stop in all contaminant producing areas until ventilation is restored; and

- Any unventilated underground area must be effectively secured to avoid entry and posted with warning signs.

The commonly suitable air flow quantities and velocities in underground Canadian mines are tabulated in Table 2-7 (Stinnette, 2013).

Table 2-7: Air flow quantities and velocities in underground Canadian mines

Location	**Quantity (m^3/s)**	**Range (m^3/s)**
Minimum airflow/worker	0.05	0.04 – 0.06
Diesel equipment	0.063/rated kW	0.06 – 1.2
Crusher	40	25 – 60
Diesel equipment shop	40	250 – 60
Lube/fuel bay	15	5 – 25
Fabrication shop	20	5 – 25
Storage area	15	5 – 25
Explosive magazine	5	0 – 10

(Stinnette, 2013)

2.20 The USA and Other Countries

The United States has an extended past of using natural and artificial cooling to combat excessive heat problems. In the 1860s, mines in Virginia City, Nevada used naturally formed blocks of ice shipped in from the mountains to cool the workings and the miners. In 1878, there was an average daily consumption of 95 pounds of ice per miner (Lord, 1883).

The United States Department of Interior recommended hot mines to conduct frequent environmental surveys and heat strain tests on miners. Wet-Bulb Globe Temperatures of 26.1°C for men and 24.4°C for women and a body temperature of not higher than 38.0°C were further suggested.

It also notes a hot worksite can be defined as a wet bulb at 0.5m/s velocity exceeding 79°F (26°C). Heat problems can be decreased in mines by using administrative and engineering controls, worthwhile work practices, suitable clothing, and PPE. Hence the following work practices were recommended:

- Increasing workers' heat tolerance by heat acclimatisation, and by growing their physical fitness;
- A work/rest schedule with frequent breaks and reasonably short work periods; and
- Rotating personnel on hot jobs, providing readily accessible cooler rest areas, cool drinking water (10°C – 15°C), and encouraging all employees to drink a cup of water every 15 to 20 minutes.

Germany has based their Mines and Safety Regulations on dry-bulb temperatures and general temperatures, and working time is restricted to six hours if more than three hours of the day is spent working at dry-bulb temperatures of over 28.0°C (Leveritt, 1998). Systems such as bulk air coolers may be installed instead of or in addition to adequate ventilation.

Coal mining in Germany this century has followed the Carboniferous Ruhr seams which slope downwards to a great depth. Work takes place at depths as low as 1400m where the environment is subject to an average temperature increase of approximately 3°C per 100m depth. It has been found in the Ruhr and Saar coalfields of Germany that the usage of air conditioning in ventilation systems has now developed into a crucial aid to climate control (Piekarski, 1995).

2.21 Ventilation on Demand

With the increase of energy costs occurring in many countries, a cost-effective mine ventilation system has become highly desirable in underground mine operations (Kurnia, et al., 2014).

Ventilation on demand (VOD) is a simple idea and requires only the minimum ventilation flow to be circulated to a particular area of a mine at a particular point in time to satisfy the ventilation requirements of providing adequate oxygen and to dilute and remove ventilation pollutants whilst providing miner comfort. Traditionally the approach has been to determine the maximum airflow requirement and to circulate this flow through the whole mine or mine section at all times. From the perspective of energy efficiency, the traditional approach has a number of failings (Tuck, et al., 2006).

Ventilation on Demand is a significant advancement in underground mining ventilation systems. VOD systems employ a series of sensors distributed throughout the mine that send real-time information regarding air quality, vehicle use, and personnel to a central computer with specialized software. Figure 2-25 shows an accutron flow transmitter and gas sensors used to sense CO and provide temperature sensor information.

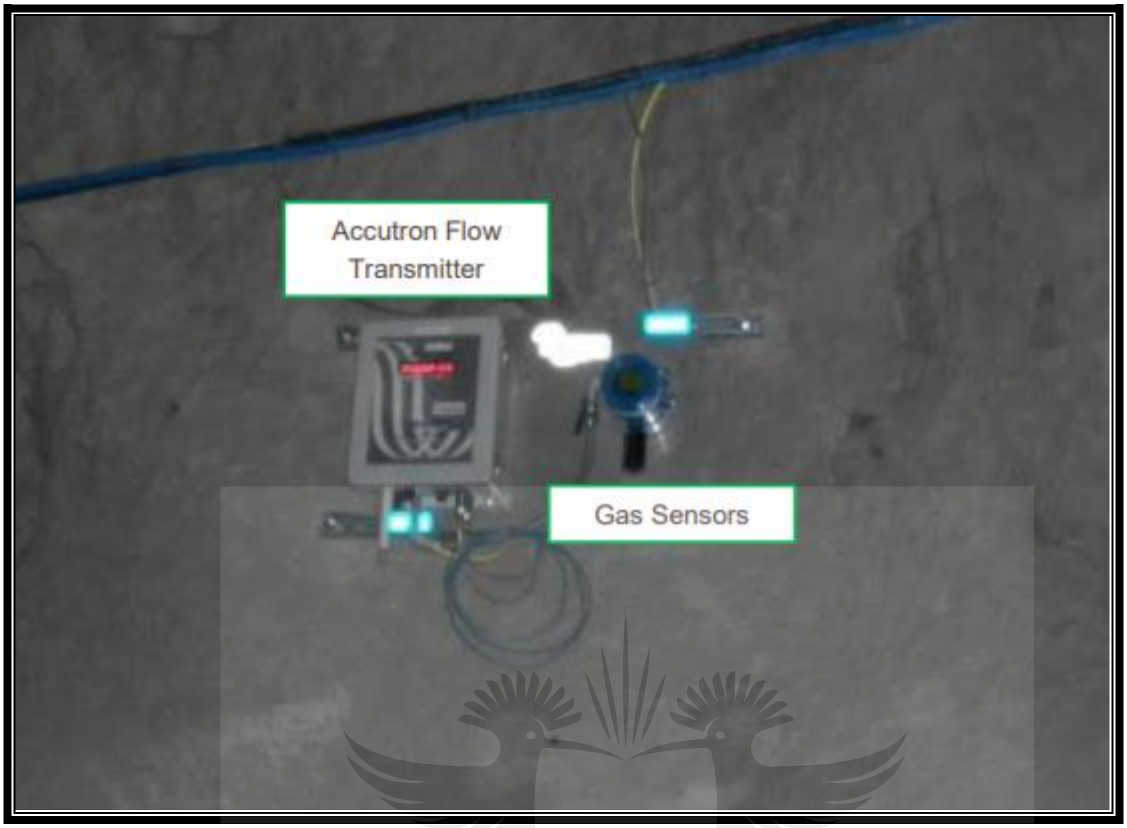

Figure 2-25: An accutron flow transmitter and gas sensors ((Mc Laren, 2013)

This technology system, combined with adjustable fan and louver controls, creates a highly adaptable ventilation system capable of substantial energy savings while maintaining air quality standards. VOD systems have successfully been implemented at mines in Ontario and throughout Canada resulting in reduced environmental footprints and substantial energy cost savings. (de Vilhena Costa & Margarida da Silva, 2020).

The concept of providing ventilation underground mines, only to the areas requiring air, in the appropriate amount, and then only as long as necessary would seem to be logical to minimize the cost associated with ventilation. Despite its apparent simplicity, for a variety of reasons, the concept has not been widely adopted by the industry. As a result, many mines operate their ventilation systems assuming maximum production, supplying all potentially active areas, and continuous operation, 24 hours/day, 7 days/week, etc. (Hardcastle, et al., 2006).

Ventilation on demand is a departure from classical ventilation thinking. Its applicability depends to a large extent on variability associated with variable ventilation requirements within the mining cycle and as such is not applicable to all mining systems (Tuck, et al., 2006).

There are two VOD strategies namely event and quality based. Event based is also known as activity based which means the air is supplied for the activity or event in a working area. Quality based is when the fans are switched on when the contaminants reach a certain level. Both strategies are essential because the machines must be supplied with air and occupational exposure limit of contaminants must be kept at an acceptable level in the underground workings (Mochubele, 2014).

2.22 Chapter Summary

South Africa's gold sector is a world leader in deep-level gold mining. Deep-level underground mining, however, brings with it risks and hazards that require constant commitment and adherence to safety and health standards and procedures. High temperatures and high humidity levels in some underground mines create stressful working conditions and can decrease productivity. A mine's cooling strategy should be intricately planned as the mine deepens and its life extends. Cooling units can be upgraded, and different combinations of cooling systems can be utilised. This is important not only for the safety and health of the mine workers but also for the sustainability of the mining industry in such a competitive world market. Inarguably much work has been carried out in the past about cooling and ventilation. As of now utilised underground cooling practices are separated into various classifications dependent on the scale of the systems. This incorporates three wide-ranging categories: central cooling, spot cooling, and micro-climate cooling. These classifications can each be isolated further into various cooling methods which differ dependent on the structure and heat of the systems (Mapeta & Rupprecht, 2019). The following chapter discusses the methods and strategies used to collect empirical data, also looking into the research approach and the research design.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter discusses the methods and strategies used to collect empirical data. The research methods include the research approach, research strategy, sampling technique, the procedure for data collection, data analysis, reliability, and validity of the methods, and ethical considerations. Mixed methods were employed for this study, i.e. both qualitative and quantitative to answer the research questions.

3.2 Research Approach

The primary focus, in terms of specialists, was to request for interviews to obtain their opinion on ventilation and cooling methods currently being implemented in underground gold mines. As highlighted in APPENDIX 7: below, the specialist's views on why past recommendations have not been implemented were noted and also the improvements that can be considered to improve the underground work environment.

This research was also keen on comparing what was gathered in the literature review with the results of the case studies. In addition, comparing the case study results with other results obtained from data provided by other ventilation specialists. Although the intended output of this research was not to provide a new set of hypotheses, nevertheless it was worthwhile in that existing theory (from the literature review) was compared against the behaviour of mines and, as a result, an improved understanding – rather than new hypotheses, was developed to aid gold mines in their quest to address underground heat issues.

3.2.1 Challenges of Using Mixed Methods

Inarguably, collecting information using both research techniques is time-consuming, and hence more resources may be required to be able to obtain both types of data. McKim (2017) affirms that mixed methods require more time due to the need to collect and analyse two different types of data. The results of the study need to be presented clearly so that readers can accurately understand the procedures and the findings (Yin, 2003).

3.3 Research Design

The research was conducted based on Mines A, B, C, and D hence it follows a case study method. The research strategy that will be used to implement the empirical research is a case study (Zainal, 2007) wherein his journal Zainal elaborates that a case study:

"…enables a researcher to closely examine the data within a specific context. In most cases, a case study method selects a small geographical area or a very limited number of individuals as the subjects of study. Case studies, in their true essence, explore and investigate contemporary real-life phenomenon through detailed contextual analysis of a limited number of events or conditions, and their relationships…" According to this definition, a case study is therefore concerned with close observation of how a population group behaves in context. The use of case study methods allows the researcher to go beyond the quantitative statistical results and understand the results from the participants' perspective.

A descriptive case study is a pre-planned and structured design that is naturally conclusive due to its quantitative nature. It is commonly used to describe an opinion, attitude, or behaviour held on a particular subject by a group of individuals. This research is descriptive because it examines deeply into ventilation specialist's opinion on environmental temperatures above 27,5°C by dedicating time and energy concentrating on specific aspects of cooling methods adapted in the mine using a structured questionnaire. This study provides the perspectives of ventilation officers on the underground environmental conditions that employees are exposed to, based on the review of the mine's ventilation reports. Hence, this research is an exploratory study.

3.4 Quantitative Method

Quantitative Research was used to quantify the problem by way of producing numerical data or data that can be converted to useable statistics. The study used numerical data to present the results of the analysis, hence it follows a quantitative approach. Large sets of data are involved, and statistical techniques are used to analyse data. This method was used, including all the quantitative techniques applied, from sampling to data analysis, to address the following objectives:

- Evaluate the current underground in-stope temperatures and the cooling methods adapted to mitigate high stope temperatures using ventilation study reports for Mines A, B, C, and D; and

- Formulate recommendations and opinions of the standard environmental conditions acceptable for efficient working conditions as well as to protect the health and safety of underground workers and improve productivity.

3.4.1 Respondents of the Study

The respondents of this study under quantitative methods were ventilation specialists who are involved in the decision making of the regulations and stipulation of the necessary measures that create a safe and productive environment for the workers. These managers and specialists have the experience and opinions acquired over time. They have also had the opportunity to hear the opinions of the employees.

It awarded the opportunity, therefore, to gain a variety of professional views to contribute to the proper conclusion of the topic by using interviews and discussions obtaining other experienced views in recognition that an underground mine is a complex environment and professional views need to be placed in context.

3.4.2 Sample and Sampling Technique

Sampling consists of a population (N) and a sample (n). A population is the object of the study; it can consist of individuals, groups, organisations, human products, or events. Involving all members of the population in the study project is generally impractical and uneconomical (Welman & Kruger, 2001).

A sample is a part of a population (Welman & Kruger, 2001). A sample in simple terms is the portion of the population that will respond to the questionnaire of this study. When using mixed methods, determining an appropriate sample size requires the researcher to balance appropriate sample sizes for both methodologies. The population size of 15 ventilation specialists was considered in the research.

3.4.3 Sampling Technique

Convenience sampling was used to select both the case studies and the specialists that participated in the discussion. It is convenient because the researcher carried out some of the discussions and interviews during the mine visit and it also depended on the willingness of the interviewee to dedicate their time. This means that the interviewees have not been chosen at random and that therefore there can be no claim to achieving representative views related to underground gold mining. Instead, this research has as its focus the aim of achieving an in-depth and qualitative insight into ventilation and cooling issues

3.4.4 Data Collection

As outlined by (Cohen, et al., 2017) it is a perfect example of the concept of triangulation where different accounts of the same phenomena (ventilation) can be compared. At a simple level triangulation is said to occur 'as the use of two or more methods of data collection', e.g. interviews and documented sources to explain more fully, the complexity of underground ventilation and cooling by studying it from more than one standpoint.

The case studies data will rely on two data collection techniques: interviews and documentary secondary data (e.g. ventilation records). The data collection technique will depend on structured interviews (detailed in APPENDIX 7: below). By gathering quantitative and qualitative data, the researcher is more likely to get a more holistic picture of the behaviour they are studying. The use of higher reliability methods such as questionnaires can offset reliability weaknesses in observational methods.

3.4.5 Data Collection Instrument

A questionnaire is a study tool that consists of a set of questions to gather information from participants. The use of structured interviews and ventilation reports was used to provide the opportunity to relate different ventilation specialists views to specific research objectives: their opinions on the use of instope atomisers for instope cooling concerning its effectiveness against these high temperatures, cooling garments as a microclimate method of cooling and its possibility of adoption into the South African mining industry, functions of the cooling car as an in-stope cooling method, elaborating on the challenges connected to it being placed in the stope, etc. The questionnaire was written clearly and unambiguously so it could be easily understood by respondents.

Structured questionnaires limit respondents to a fixed set of responses. The advantages of using structured questionnaires are as follows (Yin, 2003):

- They provide large amounts of data at low cost, allowing the researcher to interview a large sample in a short time;
- The information provided by respondents allows for statistical analysis because it can be easily transformed into quantitative data; and
- They can be readily standardised and readily duplicated to verify reliability. Other researchers may use the same questionnaire to verify whether the findings are compatible because the same questions are asked to the participants in the same order.

Although structured questionnaires have numerous advantages, they also have limitations. Due to fixed responses, the respondents are limited from reflecting on their true perspectives on a topic.

Secondary data was collected by reviewing company records. These records include ventilation reports and temperature records of cooling cars.

3.4.6 Procedure

The major focus of this research is to gain a deeper understanding of how underground temperatures can be reduced to acceptable standard levels, carry out an analysis of the adopted and recommended cooling systems in practice based on the selected case studies (Mine A, B, C, and D). Permission to conduct research was obtained from the senior human resource manager of the mine. The training managers organised the field study. The purpose of interviewing different specialists (e.g. Group Occupational Hygiene Manager, Occupational Hygienist and Ventilation Engineer, etc.) is to allow for cross-comparisons of responses, supporting different opinions of similar ventilation issues to emerge (e.g. rationale for involvement, perceived barriers, etc.). For example, Group Occupational Hygiene Manager, Occupational Hygienist will be questioned mainly on strategic and implementation issues related to underground cooling, whereas the Ventilation Engineer, although receiving questions on strategic issues, will be questioned mainly on worker's experiences, issues linked to strategic objectives, including current in-stope temperatures experienced. The interviews were recorded for two reasons: to ensure that the analysis of data is based upon an accurate record (e.g. transcript) and to allow the interviewer to concentrate on the interview as taking notes and being in charge of the discussions can disturb the flow of the interview and the result of the interview.

The following specialists were selected and interviewed based on convenience and experience in ventilation:

- Director of Mine Ventilation and Refrigeration Projects (BBE Projects);
- Underground mining consultant specialised in Mine Ventilation and Refrigeration Systems (3);
- Competency Area Manager (occupational heat stress and hearing conservation) (CSIR);
- Group Occupational Hygiene Manager;
- Ventilation Engineer (3);
- Occupational Hygienist (3); and
- Mechanical Engineer (BBE) (3).

3.4.7 Data Analysis

The essence of this research data analysis pattern was to reflect accepted practice in dealing with data, as described by Bogdan and Biklen (1982) as 'working with data, organising it, breaking it into manageable units, synthesising it, searching for patterns, discovering what is important and what is to be learned, and deciding what you will tell others'.

The interviews were structured according to themes to help align them to the objective of the research and ease the analysis of the qualitative data. These themes reflect the general aim and objectives in this research and highlight the main areas arising from the literature review: Cooling (methods), Identification of challenging (temperature) mines, Rest periods in cooling rooms, Cooling garments, Women in mining and, to conclude, Acceptable environmental standards. These topics are inter-related hence they were not viewed as separate. All the topics can be automatically placed under the heading 'The study of ventilation and cooling in gold mines to improve productivity and safety'.

For example, questions on "Acceptable environmental standards" relate specifically to how the interviewees view the 27,5°C to 32,5°C temperature range with relevance to the current underground conditions; similarly, the possible adoption of cooling garments to South African deep mines for use in hot environments is a cause of concern, as they may be useful for emergency purposes even though they are considered expensive.

Under each theme, the interviewee received a combination of open and closed questions as illustrated below.

- What do you think are the benefits of using cooling garments if any?
    - Do you know of any mine using them?
    - In your opinion is their application generally effective?
    - If so, what are the available cooling garments, and do they serve their purpose?
    - What mechanisms of cooling are the cooling garments using?
    - Are cooling garments affordable and are they personalised or shared amongst the workers?

The themes are there to help the interviewer and interviewees focus, and as an aid to the analysis of the transcripts. A breakdown of questions (including sub-questions) under each theme for the interviewee. Further, as an indication of the quest for depth, as well as focus on this research, the interviewees were asked compound questions that allow the response to be well explained and pondered upon. Hence descriptive analysis was used to analyse data from this study.

3.5 Qualitative Methods

Belle (2005) states that researchers adopting a qualitative perspective seek for a viewpoint rather than statistical interpretations of the world. This is the focal objective of the empirical aspect of this research: to understand what occurs in an underground mine in terms of ventilation and cooling, how an underground section experiencing ventilation challenges in terms of ventilation and cooling can overcome these difficulties, and, above all, seeking individual perspectives from those ventilation specialists who have been involved in ventilation issues.

Qualitative data collection methods include key informant interviews and participation observation. The sample size is typically small, and respondents are selected to fulfil a given quota. The research focused on group discussions and/or in-depth interviews with a small sample size. Secondary data of company records of ventilation reports were obtained from the mines under investigation in this study.

This methodology was applied to address the following objectives:

- Evaluate the current underground in-stope temperatures and the cooling methods adapted to mitigate high stope temperatures using ventilation study reports for Mines A, B, C, and D.
- Formulate recommendations and opinions of the standard environmental conditions acceptable for efficient working conditions as well as to protect the health and safety of underground workers and improve productivity.

3.5.1 Data Analysis

The interviews were structured according to themes to help align them to the objective of the research and ease the analysis of the qualitative data. These themes reflect the general aim and objectives in this research and highlight the main areas arising from the literature review.

The data was categorised according to themes by focusing on words frequently noted in the ventilation report. For example, if a report stated that a cooling car at a cross-cut was not functioning and requires fixing, then this response would fall under the analysis of “Cooling Cars” that were used underground. The trends in the temperatures were also noted and added to the analysis of the data obtained from the questionnaires.

3.5.2 Limitations and Strengths

The reports often had some missing data that made the ventilation report insufficient in that the Ventilation officer failed to measure all temperatures in panels during the stope visit thus potentially excluding data that could have highlighted temperatures in other panels that were possibly above 32.5°C (wb). Some reports were not written with clarity and the images of the stope were not well drawn hence they could not be used which decreased the amount of useable data. Other reports, unfortunately, did not elaborate on underground conditions and therefore difficult to understand. Table 3-1 summarises the strengths and limitations of qualitative research.

Table 3-1: Strengths and limitations of qualitative research.

Strengths of qualitative research	Limitations of qualitative research
Most of the temperature values recorded were confirming the difficult conditions that mineworkers operate under.	The sample size for this approach was small, therefore, it is difficult to generalise.
The approach considered the reported data perspectives.	It is possible to assume that the omission of some of the missing panel temperatures was intentional to avoid exposure of the real stope temperature.
The reports originated from two different gold mines	The reports were only 10, more of them would have been useful.

3.6 Validity and Reliability

Mines A, B, and C were viewed as ideal mines to use as case studies, then, to complete the analysis of underground ventilation, data from Mine D needed to form part of this research so as to provide a complete picture. To concentrate solely on Mine A (case study) would produce a myopic perspective: Use of cooling car temperature recordings and views of 15 interviewees. To gain a fuller perspective, the research required to be widened to include data from other Mines.

There are two other reasons for choosing Mine A as the Case Study, Mine A is one of the deepest mines in South Africa, mining deeper than 3000m. It is for this reason that cooling has been essential and inevitable, making it an ideal mine to use for this Ventilation research study. Mine B and Mine C have positional favourability in the research. Including the Mine D extension programme also permits the incorporation of relevant knowledge to the research.

Each question in the questionnaire was linked to the study objectives and each respondent received the same questionnaire with the same set of questions to ensure validity and reliability.

3.7 Pilot Study

The questionnaire for this study was given to three mining employees in the production sections to participate in order to:

- Evaluate the time required to complete the questionnaire;
- Check whether the instructions were clear;
- Check for any ambiguous statements; and
- Check whether the content of the questionnaire caused them any discomfort.

The participants' feedback was used to improve the quality of the questionnaire. The benefits of undertaking a pilot survey are that it warns where the questionnaire may fail, shows any complexity or inadequacy of the questions, and identifies where research protocols may not be followed.

The following feedback was received from the pilot study: (1) the questionnaire is too long due to the repetition of some of the questions, (2) the absence of an introductory statement was a disadvantage, as the interviewees did not know the purpose of the research.

3.8 Ethical Considerations

Research involving human participants raises ethical, legal, social, and political concerns. Research ethics relates to ethical problems raised when a study involves human beings. There are three objectives in research ethics: to protect the participants and ensure no harm, to research a way that serves the interests of individuals, and to ensure confidentiality and informed consent (Denscombe, 2014).

Benatar (2002) alludes that ethics are described as standards of behaviour that distinguish between acceptable and unacceptable behaviour. The following principles of ethics were applied:

- Autonomy: The questionnaire clearly stated on the cover page that the participants were not compelled to participate in answering the questionnaire and if they did agree to participate, they were free to withdraw at any time. The questionnaire did not require personal information such as identity details, clocking numbers, contact numbers, or home addresses. The completed questionnaires were stored in a password-protected file and all the information was kept confidential;

- Beneficence: There was no financial reward given to participants for taking part in the questionnaire. However, the findings from this study will assist the management in identifying work-related issues that may contribute to hot working environments;
- Non-maleficence: The information from the questionnaire was not used to jeopardise the participants' employment and was not shared with any individual or company. The questionnaires were stored in a password- protected file and it would be impossible to identify the participant if they were to somehow be accessed by an unauthorised individual; and
- Justice: The questionnaires were distributed in such a way that the participants did not feel compelled to participate. It was ensured that those that chose not to participate did not feel like their jobs were in jeopardy. The questionnaire was clear and unambiguous in ensuring that participants understood that the purpose of their participation was purely academic and would not affect their employment.

3.9 Chapter Summary

This chapter discussed the research methodology followed in the study. It also presented the research design, sampling strategies, measuring instruments, pilot study, and ethical considerations. This study applied a mixed-methods approach, which is also known as triangulation. The research design adopted was that of case studies as the research focuses only on specific organisations. Both simple random and accidental sampling techniques were applied to select the part of the population. Questionnaires were used as the research instruments to collect data from subjects. This study considered ethical responsibilities as required by the nature of this research. The following chapter presents the results of the research based on the case studies (Mine A, B, C, and D).

CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter presents the results of the research based on case studies (Mine A, B, C, and D). The research concentrates on underground ventilation in gold mines. It focuses on the opinions of ventilation specialists in the mining industry to gather information on the current status of hot gold mines.

4.1 Case Study: Mine A

Mine A case study is approached in a highly structured way. First, a description is provided of the mine, then opinions of the ventilation management stuff are put together.

4.1.1 General Description

Mine A is located in the Free State, a gold underground hard rock mine using the conventional breast method to extract the ore. In addition to the normal ventilation system, the mine uses ice for cooling. The ice plant receives municipal water at about 27°C and the water is cooled down to between 6°C and 9°C. The water leaves the ice plant and reaches the stope at between 14°C to 20°C. Mine A has adopted cooling cars as a method of cooling the stope.

The cooling cars are located at the crosscut close to the stop entrance. They are meant to cool the air as it enters the stope from the surface. However, they are misused as shown in Figure 4-1 where the chilled water pipe that supplies chilled water to the cooling car is taken out and placed on the ground so that the chilled water coming out of it can be used for other uses, leading to system inefficiencies.

Figure 4-1: Improper use of a cooling car positioned at the stope entrance at Mine A

Mine A has two shafts. One of them is used to hoist rock and the other serves as a second escape route. Mining is conducted at a depth greater than 2500m.

Observations of the cooling and ventilation methods applied in their hot stopes were noted and opinions of the effectiveness of these methods according to the interviewees were also recorded. In the discussions, the challenges being faced, and their suggestions on the solutions were raised. The mine experiences challenges such as poor mobility and the failure of mine personnel to take good care of the atomisers. It is reported that the atomisers are said to be rigid and are not easily moved around. Unfortunately, it results in employees forgetting them in the stope when they finish working there and they are left behind only to be accidentally destroyed during blasting. The effectiveness of in-stope atomisers in temperature reduction is also low; the atomisers are said to reduce the air temperature by about 1°C or 2°C at most. This is a small decrease in hot stoping environments. The efficiency of these atomisers becomes questionable. Deepmine Task 6.6.1 has shown that in-stope air coolers could realistically achieve water efficiencies of up to 60% (Butterworth, et al., 2001).

The following in-stope cooling systems were also discussed:

- Rest periods – These are not practiced at Mine A and in general it was anticipated that employees do not enjoy interruptions when carrying out their work and therefore they would only use up their rest period at the end of the shift the reason being that they feel they might not be able to meet their daily targets if they had to stop, thus defeating the intended purpose;
- Cooling rooms – These have not been trialed at the mine. It is however feared that some employees would misuse such facilities for prolonged periods because the conversations can possibly be extended;
- Cooling garments – These garments were said to be expensive for a mine in the upper quartile in the cost curve as Mine A. It was also suggested that the workers would neither be keen to have extra weight on them as they are working since they already have to carry the rescue pack on them etc; and
- Pipe insulation – Although this is not limited to the in-stope environment, Mine A is currently undertaking it (APPENDIX 2: below). They have also raised the issue of the process as being expensive. A chilled water pipeline of a 200mm internal diameter steel pipe costs approximately R600 for every 2m (2020).

4.1.2 Discussions and Interviews

In the discussions and interviews, the occupational hygienist person suggested that reducing the high in-stope temperatures is possible, but the challenge is cost related. He remarks "…If the temperatures can be below 28°C we will be covering the safety aspect and the productivity because errors are happening around 28°C... we stop at 31,5°C to fix the ventilation but people can continue whilst we fix". Mochubele (2014) supports the fact that maintaining rejection temperatures of working areas below 27.5°C comes at an unreasonable cost given the electricity price hikes. Recent studies revealed that underground ventilation and cooling accounts for 30% to 40% of total electricity costs in an underground metalliferous mine (Mochubele, 2014). This explains why most mines carefully choose a ventilation strategy that sets the rejection temperature at the upper scale, in a range of 28°C to 29.5°C (wb). As noted previously such temperatures are not safe for workers because their level of concentration starts to decrease, and it can increase the chances of accidents occurring.

Specifically, for women in mining, in a discussion with Ross Wilson (2018), a director of Bluhm Burton Engineering (BBE), he alleges "…my first opinion is that nobody should be working above those temperatures but if it's not safe for women it's not safe for men..." This statement is true but does not show much attention to the obvious differences between men and women's physiology. However, as women are now getting more involved in working in underground conditions it remains essential for research to continue to ensure safe working conditions for them. This is because mining initially comprised almost entirely of men but over the years some women have developed an interest in working underground.

It was an issue when women first started mining, but the management confirms that in the last couple of years, they have had them incorporating even past the stage of shift boss in operation as well, besides the available number of miners. The simple reason is that the "target tonnage does not change you just have to deliver or else the job opportunity is lost. The management further elaborates that women are safe in their mining environment as they are also a part of structures where they meet on a regular basis …they go and discuss issues related to mining amongst themselves…" The manager clarifies that at this point mining is no longer a gender issue due to the heat screening test that is performed before someone can be allowed to work underground. Rather it is a matter of an individual being heat tolerant then they can be permitted to work. Additionally, it is important to note that the heat tolerance test for women is not the same as that for men which is part of accommodating females in the mines, as per health and safety law.

To achieve safe temperatures, Mine A has installed in-stope atomisers inside most of the panels to spray the environment which is part of the Mining Industry Occupational Safety and Health (MOSH) initiatives.

Initially, atomisers were used at dust plots around the mine. “We have done a lot of work on the tips because that is where we create much of the dust, where we have put in atomisers, tip covers, filters, etc. So, you wouldn’t get a lot of dust there the dust is now inside the stope. That is where these instope atomisers came from as a leading practice. At first, before installation, it was 30% compliance in terms of dust but when we installed them it moved up to 60% by just installing the atomisers. So, they do work but they depend on people to move them as they are not heavy” suggested the ventilation officer.

Group Occupational Hygiene Manager alludes “…but remember cooling comes from two things: the temperature and the velocity. This means that in a panel of 29°C with a velocity of 0.8m/s the guys will love it. On the contrary 27°C and velocity 0,1m/s, the guys will not be comfortable working in it. Also, the mine standard for this mine is 0.4m/s velocity”. The Australian Regulations states that: in any workplace in an underground mine, and any tunnel under a surge stockpile on the surface of a mine, the manager of the mine must safeguard that: if the wet bulb temperature surpasses 25°C, an air velocity of not less than 0,5m/s is provided. (New South Wales Government, 2014). Any manager may prepare and implement a code of practice on any matter affecting the health or safety of employees and other persons who may be directly affected by activities at the mine (Department of Mineral Resources, 1996).

To conclude on their choice of cooling systems, the main question that remained was on the efficiency of these instope atomisers. The management is of the opinion that “it depends on the temperature you start with. If you start at 35°C and it drops a degree you will not feel it. And if its 32°C and it drops a degree you will feel it or 31°C to 30°C or 30°C to 29°C” explained the mechanical engineer.

Such a reason for efficiency leaves the instope atomisers as a doubtful system to adopt in these high temperatures. Mine A considers a more effective cooling system that can cater to any temperature range. Additionally, mine A is not considerate for safety given its position through management.

Past experiences have proven to this mine that stope coolers would not work for them as any system that depended on workers to function would be additional work to the stope workers that they are not willing to take up because they are more focused on their target. Hence, they would “…conveniently forget it” in the stope and would be destroyed during blasting. The Mine also has about 15 spot coolers of 570 mm (≈R55000) and 760 mm (≈R80000) (2018) weighing approximately 60 kg-80 kg. This is also a big loss if one is left in the stope and accidentally gets destroyed during blasting.

The manager abruptly showed disinterest in the use of cooling garments as a method of micro-cooling. He believes that they are expensive and having approximately 4000 employees with each having their own would be an unnecessary cost that can be avoided. His view is rather incorrect as cooling garments can be of use especially if the employee is working in an environment of high temperatures (above 32,5°C) for a couple of hours (Schutte, et al., 1994). This can help to prevent the possible occurrences of heat illnesses allowing the worker to be safe and productive.

The cooling capacity of the cooling cars Figure 4-1 and APPENDIX 4: at Mine A are designed at 500kW but they perform at a capacity of 320Kw-350Kw. This is due to the challenge in maintenance. The easiest thing would be to have a service level agreement with the manufacturer "...They switch it off, taking out the coil, take off the hoses, and attend to the clogging caused by the dust, etc..." The Occupational Hygienist further states that the miners will not have the time to clean it up which is what causes the need for the frequent replacement of these cars.

Additionally, the mine also experiences, some leakages as captured during a mine visit, images are shown in APPENDIX 1: below. Leakages if not managed can generate humidity in the crosscuts and haulages and potential mud rushes in stopes and orepasses.

4.1.3 Heat Stress Incident at Mine A

Employees were exposed to heat related conditions on levels 69.71.73 and 75 during the period from January 2019 to April 2019. The employee did not follow mine procedure after reportedly coming from underground complaining of not feeling well due to heat.

Following is a quotation of the COP according to instruction ATP/2015/08/11 that was to be implemented under such conditions (Department of Mineral Resources, 2015):

"Emanating from the audit on 09 May 2019 where there has been evidence of employees exposed to heat related conditions at work from various workplaces, you are instructed to:

- Conduct a comprehensive investigation with immediate effect on the whole mine concerning environmental conditions and especially heat related issues;
- Such an investigation must be conducted with the aid of an independent consultant, the mine's Health and Safety Structure and organised labour unions and a presentation done to the office of the Principal Inspector of Mines with regard to among others; the findings and a plan of action to ensure that employees are safe to continue their work and recurrences will be avoided; and

- The employer is further instructed to ensure that employees who come from underground after complaining of not feeling well follow the procedure as per mine procedure with regard to reporting of accidents and incidents".

4.1.3.1 Below are Responses from Mine A

In relation to the occurrence of the heat incident the Mine had to carry out the following procedures (Figure 4-1):

- A comprehensive audit was conducted on the ventilation conditions of all the working places at Mine A; and
- Certain operations were used to compare available cooling and ventilation against actual.

Table 4-1: Summary of responses from Mine A

	WORKING PLACES AUDITED	WORKING PLACES FOUND IN ORDER	SUBSTANDARD WORKING PLACES
STOPES	62	60	2
DEVELOPMENT ENDS	21	20	1

It was also essential for an audit to be carried out and the following observations were recorded:

- Development ventilation column leakages were identified;
- Missing/damaged centre gully brattices were identified;
- Substandard dip and strike controls were identified; and
- Damaged ventilation doors were identified.

4.1.3.2 Sequence of Events

From January up to May 2019, 22 employees reported to the Medical Hub with cramps. 9 Employees were confirmed to have experienced heat cramps and one case of heat exhaustion. The Occupational Hygiene department and Unions investigated 22 Incidents. Results from a doctor's analysis show that 12 cases were not heat related. From the 10 that were confirmed 4 of the working place environmental conditions were measured above the action level of 31.5°C (wb).

To attend to the temperature challenges that occurred in the 65 74 B X/cut, where a substandard temperature was measured a 570mm spot cooler was installed. In the 63 75 Winze, a high intake temperature was noted caused by leakage from 73 74 X/cut, this leakage was sealed off. Substandard temperatures caused by substandard ventilation controls were recorded in 63 64 N6, these controls were fixed. In 65 41 S9, the fan had burnt out to solve this issue another one was replaced. Additionally, the 75 73 stope had a damaged ventilation column but it is unclear if it was fixed. The 75 69 S11, poor ventilation controls, and restriction at the top holing of the panel were neither clearly stated as fixed. Lastly, the 75 35 raise which had damaged ventilation columns was attended to.

4.1.3.3 Incident Review: Contributing Factors to the Incidents

Certain factors contributed to the occurrence of the heat incident such as subclinical medical conditions. This can be the case because subclinical disease has undetectable symptoms or produce effects that are not detectable by the usual clinical tests. Another factor is improper rehydration due to the poor availability of water sources. This can be caused by the drinking taps being a distance away from the working area.

4.1.3.4 Basic Causes:

The causes of the heat incident can be categorised into two groups which are personal factors and system failures.

In the category of personal factors, inadequate involvement by leadership to prevent the incident can be a cause for the incident. Crews were allowed to work in substandard environmental conditions. Also, poor judgement can be a reason because the employee did not report to the Medical Hub.

The system failures categorises involves continuous risk assessment where over inspections of environmental conditions were conducted inadequately. Finally, incident/accident reporting showing that the employee did not report to the Medical Hub.

A brief summary is shown in Table 4-2 it states the action taken or to be taken and the due date of completion. Of the 9 issues briefed in table 5 of them had already been completed.

Table 4-2: Summary of Action Taken and the Due Date

Number	Action taken/To be taken	Due Date
1	75 74 B X/cut, Spot cooler installed	Completed
2	73 75 Winze, leakage from 73 74 X/cut which was sealed off.	Completed
3	73 64 N6, ventilation controls which were installed to standard.	Completed
4	75 41 S9, burnt out fan was replaced.	Completed
5	75 73 Stope, busy replacing the damaged ventilation column	20 May 2019
6	75 69 S11, busy blasting the top holing	15 June 2019
7	75 35 raise, damaged ventilation column was replaced	Completed
8	No work to be conducted in any working place with substandard environmental conditions other than rectifying the ventilation controls.	16 May 2019 Daily
9	Employees that are sick or injured will be accompanied to the Medical Hub	16 May 2019 Daily

Total available cooling at Mine A includes a 55L water cooling circuit and a 55L fridge plant circuit. There is also a surface ambient air cooling. Total mine heat load is from production heat, auto compression heat, and metabolic heat. The reject temperature used is 29.5°C.

4.1.3.5 Ventilation Quantities Availability to Workings and Development

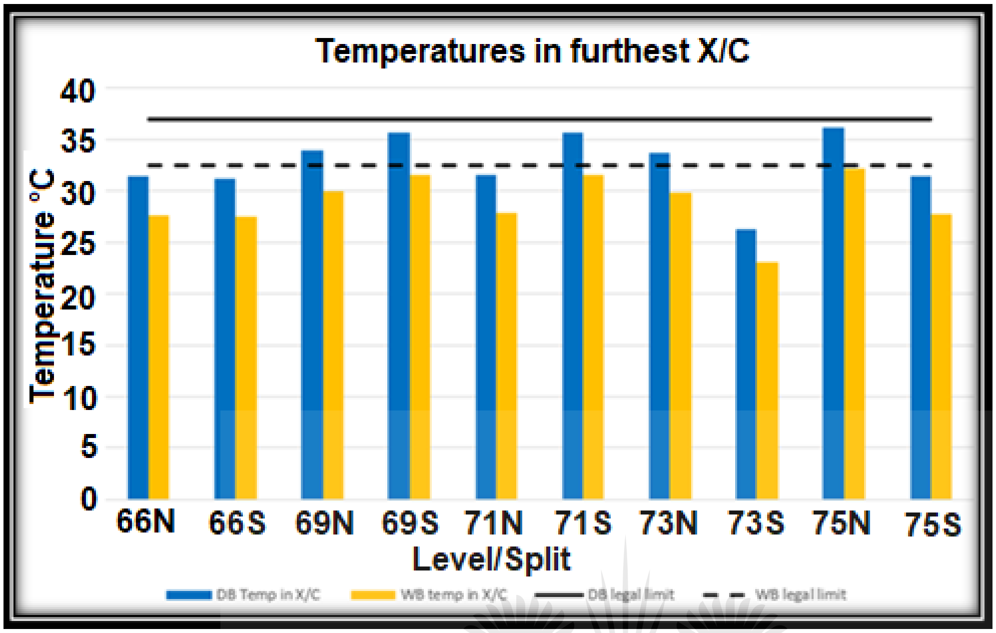

Figure 4-2: Graph from Mine A showing temperature in furthest cross cuts

The graph (Figure 4-2) shows temperatures measured in furthest cross cuts.

4.1.4 Representation of the Data Collected at Mine A

The data obtained from Mine A has been used to create graphs that will enable the analysis of the mine temperature ranges, the effectiveness of the cooling methods implemented, and evaluate the relevance of the temperature limits in connection to the reality experienced by the workers.

Figure 4-3 is a bar chart representing the different temperatures recorded from distinctive development stopes. Out of 19 stopes represented, only three (3) stopes are below or equal to the minimum temperature of 27,5°C. Two of these stopes are quite close to the upper limited of 32,5°C with values of 31,9°C and 31,6°C, respectively.

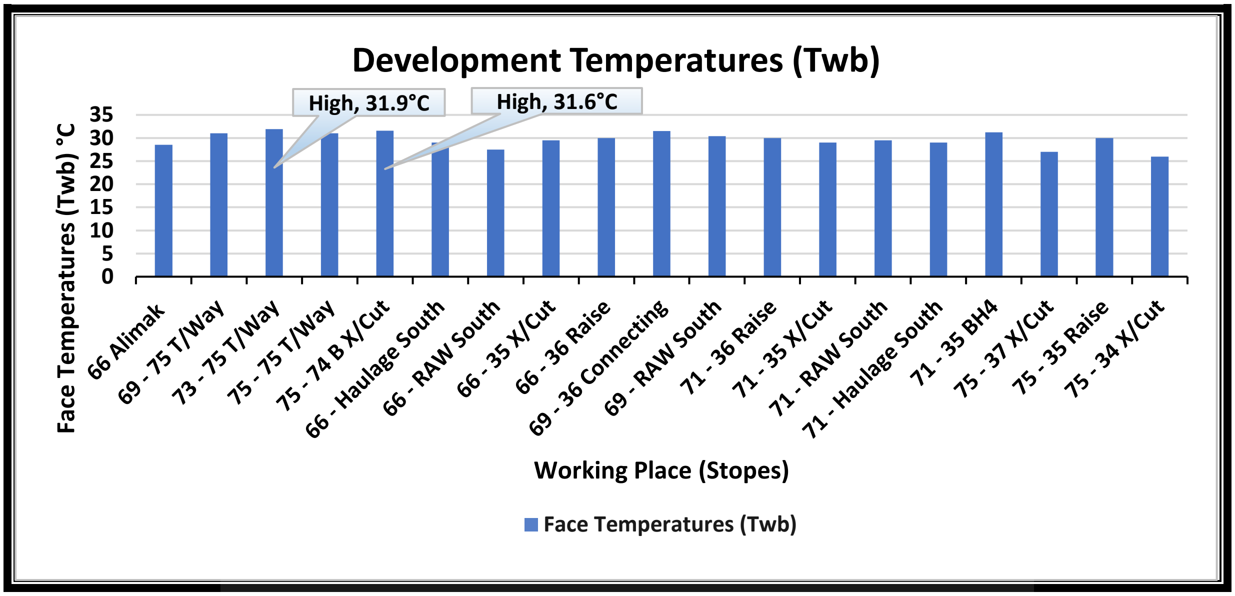

Figure 4-3: Temperatures recorded from distinctive stopes

In an interview one of the ventilation specialists admits that it is possible to bring the temperatures to below 27,5°C but it will be too expensive and keeping the temperatures below 32,5°C is not the major concern but the issue is that of discipline. When designing the mine, one designs the mine with the reject temps of 29°C. The air can be provided for, but it must be controlled and conserved.

Figure 4-4 shows face temperatures in the workplace (stope). The highest three temperatures are 31,8°C, 32,0°C, and 32,0°C respectively with none of the stopes reaching 32,5°C. Of the 51 stopes represented only ten of them are close to 28°C the rest have temperatures above this value.

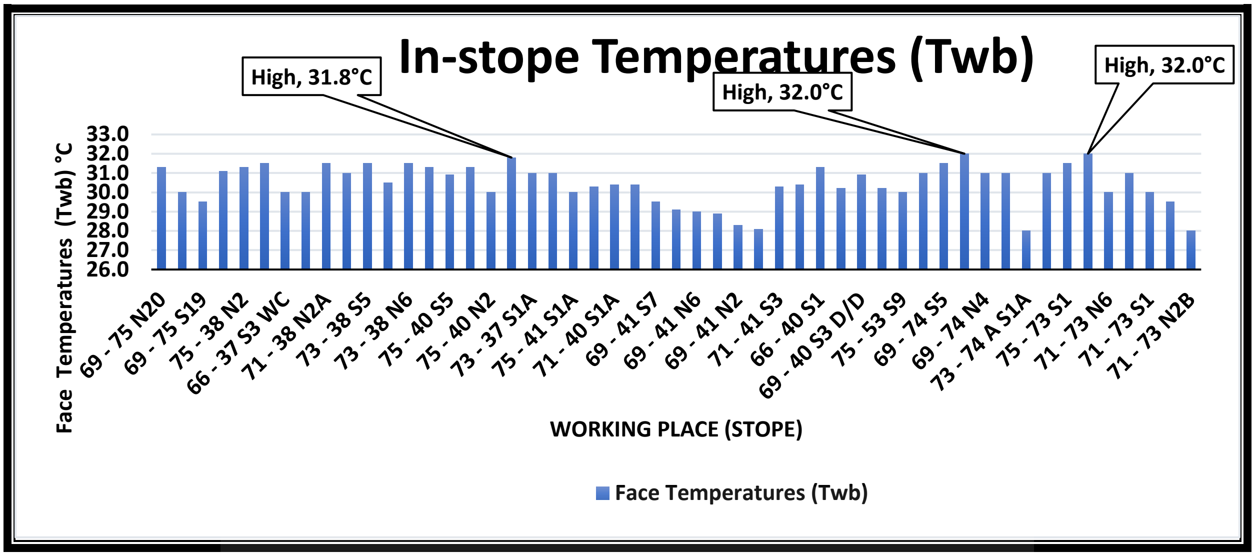

Figure 4-4: Graph showing in-stope temperatures

Stope atomisers are used to control in-stope dust which is found in the air. They are installed in the main travel ways in the stope but not at the face. The stope atomisers were also found to provide an additional benefit of cooling the immediate area adjacent to the spray (atomiser).

Temperatures are measured at the beginning of the shift progressively as you walk into the mine until you reach the working development face. Of the 61 development ends represented in Figure 4-5, one is above the limit with a value of 33,5°C and the second highest with a value of 32,0°C. The greater number of these stopes is above 27,5°C ranging closer to 29,5°C. It should be noted that this audit was scheduled and therefore the stope supervisors were most likely given a warning prior to the actual ventilation surveys. Hence, the results provided here may be slightly more optimistic than actual working conditions as seen in ventilation reports analysed in Section 4.2.

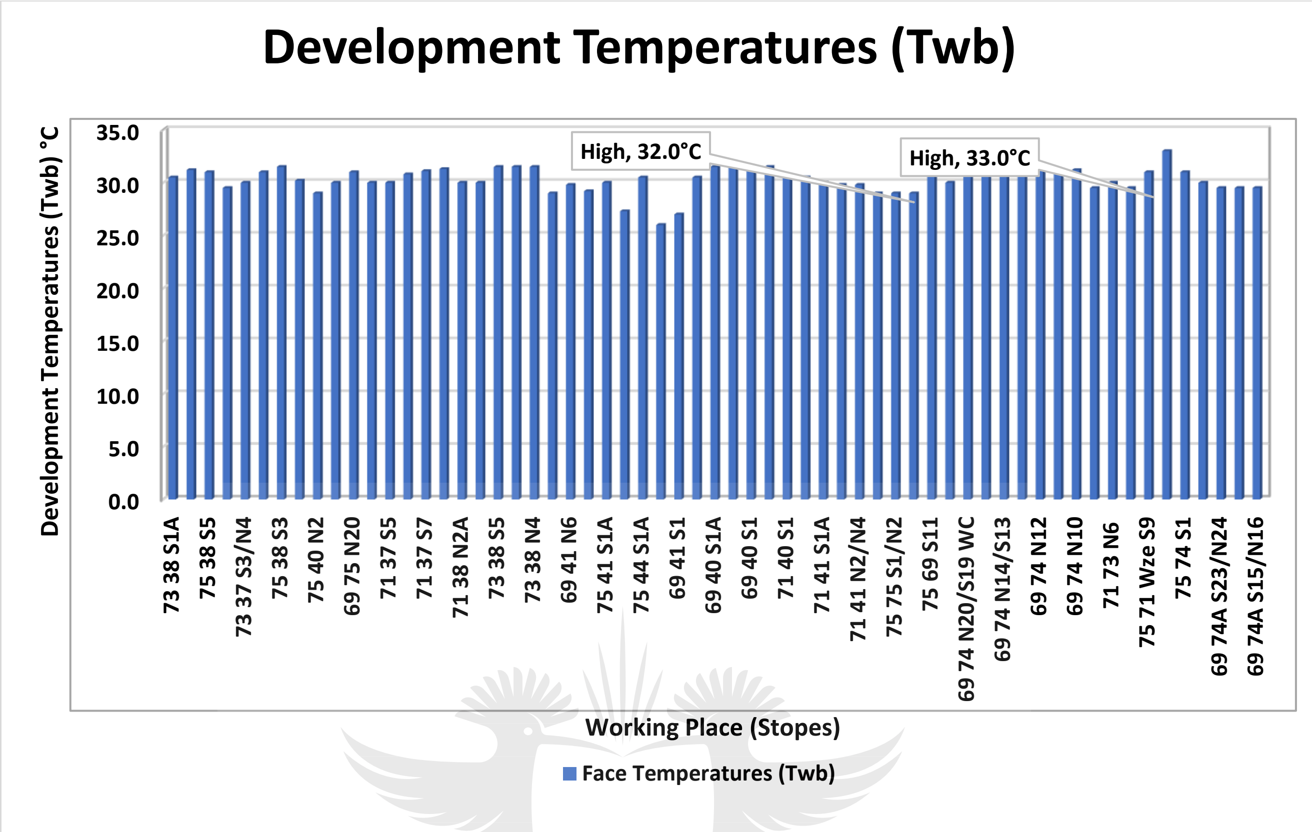

Figure 4-5: Development temperatures (^{0}C)

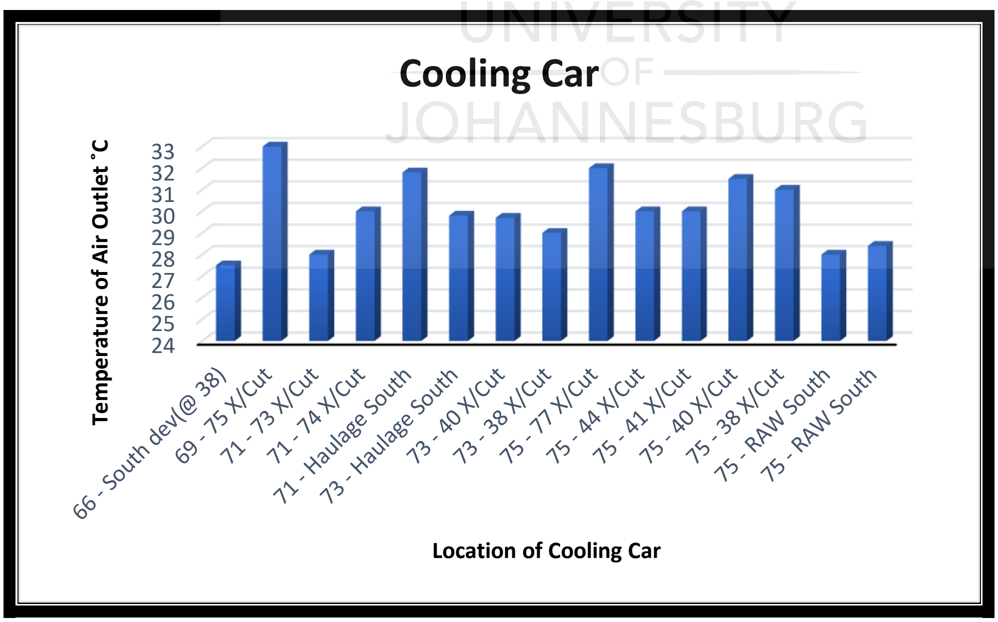

Figure 4-6: Temperature of Air Outlet of a Cooling Car

Figure 4-6 shows the temperatures that were measured for the air outlet from a cooling car. The highest temperature is 33°C and the lowest is 27,5°C. The average temperature is approximately 30°C.

The cooling capacity of the cars at Mine A has a capacity of 500Kw but provides an efficiency of 320 Kw-350Kw. At the six positions where the cooling cars are placed (Figure 4-7), the water outlet temperature is above 27,5°C with the highest temperature being 32,9°C. The lowest temperature is 21,0°C. The higher the water outlet temperature the more efficient the cooling car is of taking the heat out to the air. However, what happens to this water is also important because it will add heat back into the environment if not well managed, it should be immediately picked up by a pump and sent out of the mine. The above graphs provide an understanding of the temperatures experienced underground at Mine A. It is encouraging that the temperatures do not exceed 32,5°C but the low efficiency of the cooling car can be the reason for the water temperature outlet.

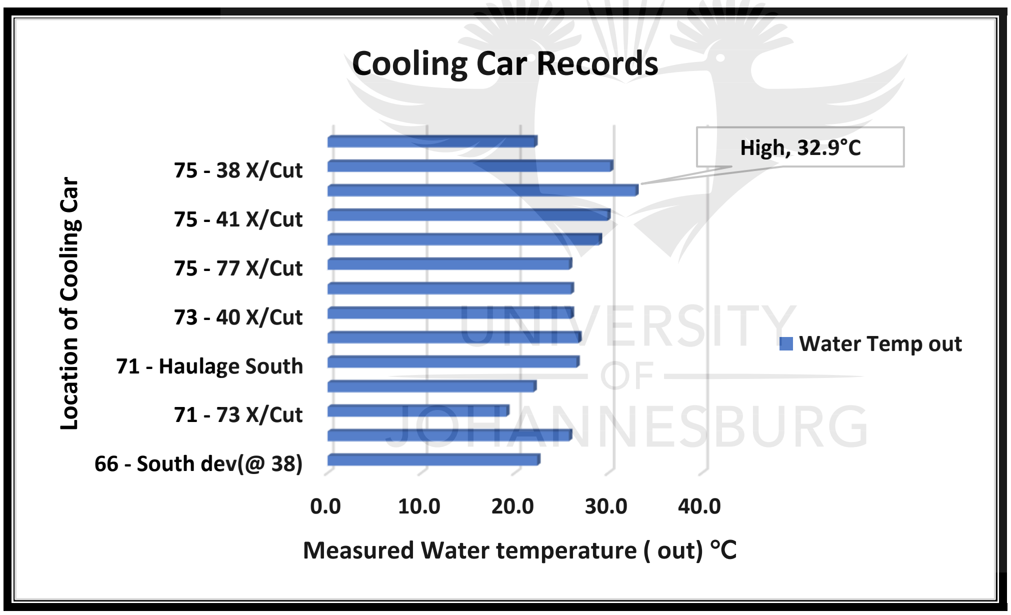

Figure 4-7: Cooling car records in different underground positions

4.2 Ventilation Stope Analysis

This section provides a ventilation analysis of stoping conditions found on Mines A, B, C, and D that are operating in less than ideal conditions and represent conditions over an 18 month period also representing the majority of the mine's operating conditions.

4.2.1 *Case Study: Mine A*

Mine A case study ventilation reports that were obtained from the Mine were analysed so as to draw a general view of the current underground environmental conditions that the workers are exposed to.

4.2.1.1 General Description

Mine A is located in the Free State as shown in (Figure 1-1). It mines the Basal Reef to a depth of approximately 2500m. It is serviced by hoisting a shaft located 5.5 km away and which is also used as a secondary escape route. Ore mined at Mine A is processed at a processing plant that is located some 20 km away.

4.2.1.2 Mine A - Diagram 1

The ventilation report (Figure 4-8) highlights the temperatures and velocities that are servicing two development ends that are reporting face temperatures of 30/35°C (wb/db) at 2.7m/s and 29.5/32.5°C (wb/db) at a minimum velocity of 0.32m/s. From this ventilation report, it can be seen that the fans are providing a sufficient volume of hot air +30°C (wb), however, the one development end is not receiving sufficient volume of air (0.32m/s). In addition, no cooling cars are in use resulting in development workers operating in temperatures that are conducive to heat stress and potential harm as worker's cognitive ability drops when temperatures exceed 29°C (wb).

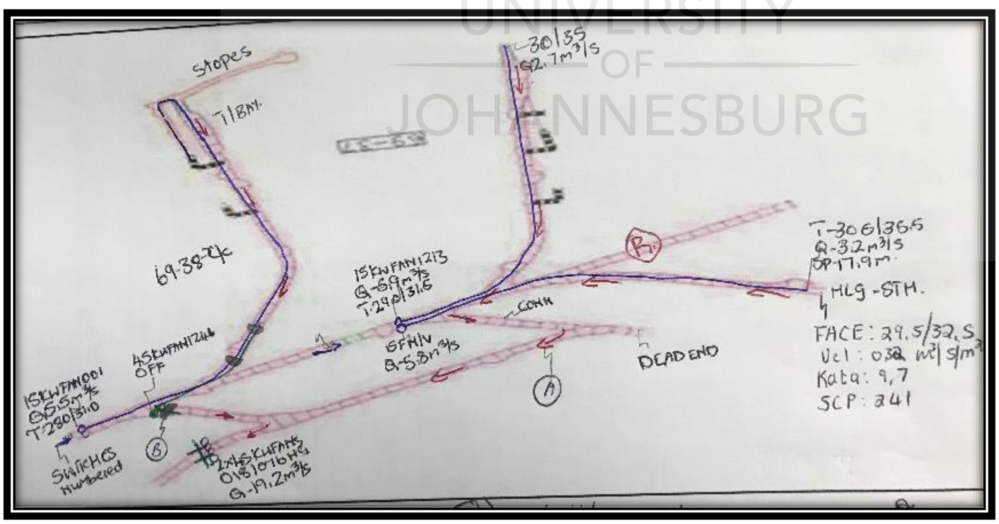

Figure 4-8: Ventilation stope for Mine A

- At position “B” (Figure 4-8) the 45Kw fan is not operational and therefore not adequately exhausting air from the stope 69-38 stope. If workers open the ventilation doors at this cross, then the return air from the 69-38 stope will be mixed with the 28°C (wb) intake air for the two development ends resulting in higher temperatures than the current +30°C (wb) temperatures;
- Although the wet bulb temperature has not reached the legal limit of 32.5°C (wb) it certainly is conducive to heat stress conditions and creates a working environment that is not suitable for good productivity and neither supports worker’s safety; and
- The ventilation department should ensure the sealing of leakages as it can be a method useful to reduce intake temperatures. A cooling car should be used to reduce temperatures in the development ends.

4.2.1.3 Mine A - Diagram 2

Figure 4-9 shows a working environment that is not suitable for the safety of the employees. The stope ventilation report highlights the following:

- The upcast air from the stope is 34.0/36°C (wb)/(db) with a velocity of 0.6m/s. The reported temperatures are well above legal limits and are conducive to heat stress as well as heat stroke. The working environment is not suitable for good productivity and threatens the safety of the employees;
- It is worth noting that the atomiser at the top of the stope has been installed to reduce dust, however, it can be observed that the atomiser has also reduced the temperature from 34.0/36°C to 31.0/34°C (wb)/(db), A reduction of 3°C (wb)/(db);
- To improve the cooling in the stope (Figure 4-9) the ventilation department should ensure that the installation of the cooling car is completed; and
- The production department should ensure that the ventilation doors at “A” are completely installed to direct sufficient air to the face.

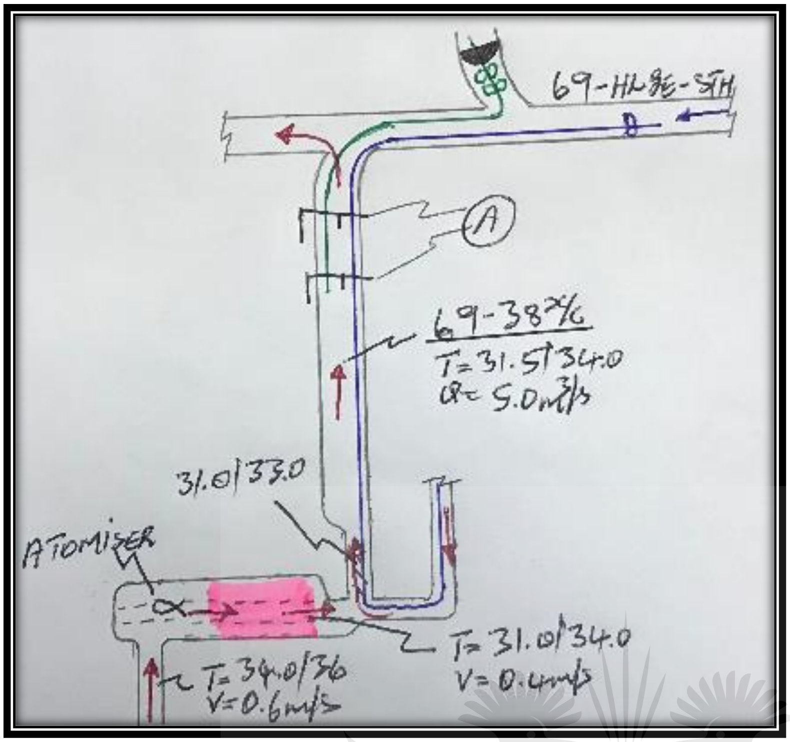

Figure 4-9: Ventilation Stope for Mine A

This report demonstrates the harsh working conditions that employees are exposed to due to inadequate ventilation systems which can cause heat stress. The temperatures are above the legal limit of 32,5°C (wb) and are unsafe and under these conditions, the stope temperatures can increase the chances of accidents occurring. The above stope ventilation conditions are conducive to heat stress and even heat stroke conditions.

4.2.2 Case Study: Mine B

Mine B case study ventilation reports were analysed, identifying the methods of cooling adapted, noting the underground temperatures experienced, etc.

4.2.2.1 General Description

Mine B is located in the Free State, near Odendaalsrus, it comprises of a single vertical shaft extending to a depth of 2154m. Ore is transported to the plant, located some 23 km away. The project will extend mining to a depth of 2490m.

The mine undertakes conventional undercut mining on the Basal Reef. The B reef is exploited as a high grade secondary reef.

4.2.2.2 Mine B - Diagram 1

Analysis of a ledging stope that is shown in Figure 4-10. This section of the underground mine shows fans and a cooling car that are used to lower the temperatures in the stope. The stope ventilation report highlights a number of issues.

- The effectiveness of the stope cooling system i.e. the cooling car in the cross cut is largely ineffective in that the intake air temperature is 27.0°C (wb) and the output temperature from the cooling car 26°C (wb). A reduction of only 1.0°C (wb). One would expect a drop of 3°C to 4°C (wb). In addition, the chilled water servicing the cooling car is 16°C (wb) which is above the 12°C (wb) target for intake service water;
- The stope air after servicing one panel (see point A and 1 in Figure 4-10 has increased from 26°C (wb)to 29°C (wb) with a very low face velocity of 0.4m/s;
- By the time the air reaches the end of the second panel (Point 2 in Figure 4-10), the temperature reaches 31°C (wb) and the face velocity of 0.4m/s;
- Although the wet bulb temperature has not reached the legal limit of 32.5°C (wb) it certainly is conducive to heat stress conditions and creates a working environment that is not suitable for good productivity nor supports a zero-harm environment;
- Notably, the stope is serviced by a fan at the start of the cross cut. If for any reason the fan would stop, e.g. fan or electrical failure, the stope would certainly rise above the legal limits;
- The lack of ventilation brattices is a concern and has a material effect on the low face velocities and high stope temperatures; and
- The ventilation department should have made further measurements on the first panel, third working panel, as well as at a position in the raise where the fourth panel would be situated. In this way, mine supervision would have a full view of the stope conditions, especially the third panel which may have a temperature above 31°C (wb).

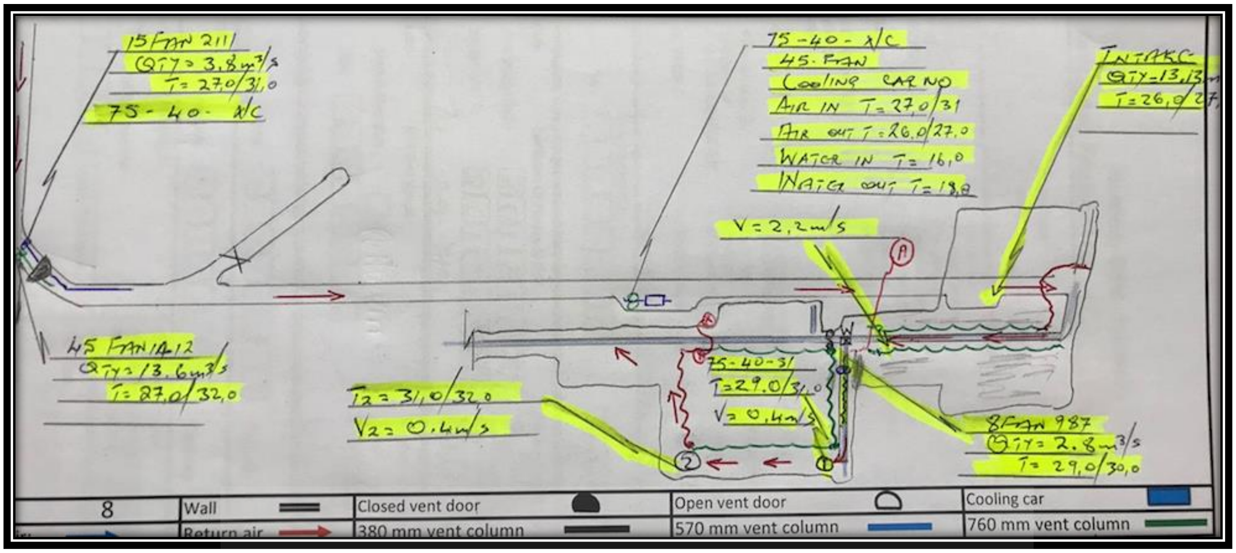

Figure 4-10: Analysis of a ledging stope for Mine B

The above stope ventilation conditions are conducive to heat stress and perhaps even heat stroke conditions. The ventilation report is insufficient in that it fails to measure all panels during the stope visit thus potentially excluding data that may highlight temperatures in other panels that could be above 32.5°C (wb). This manner of reporting does not promote zero harm for mine workers.

The efficacy of the cooling car is questioned as is the inlet temperature of the chilled water. Further, ventilating a stope with a fan is not best practice, as if the fan is out of order either the stope will receive inefficient volumes of air or stope workers will be forced to open the ventilation doors and negatively affect stopes operating beyond the cross cut.

4.2.2.3 Mine B - Diagram 2

Analysis of a ledging stope that is shown in Figure 4-11. This section of the underground mine displays a few challenges such as the occurrence of leakages and the need to install a ventilation door.

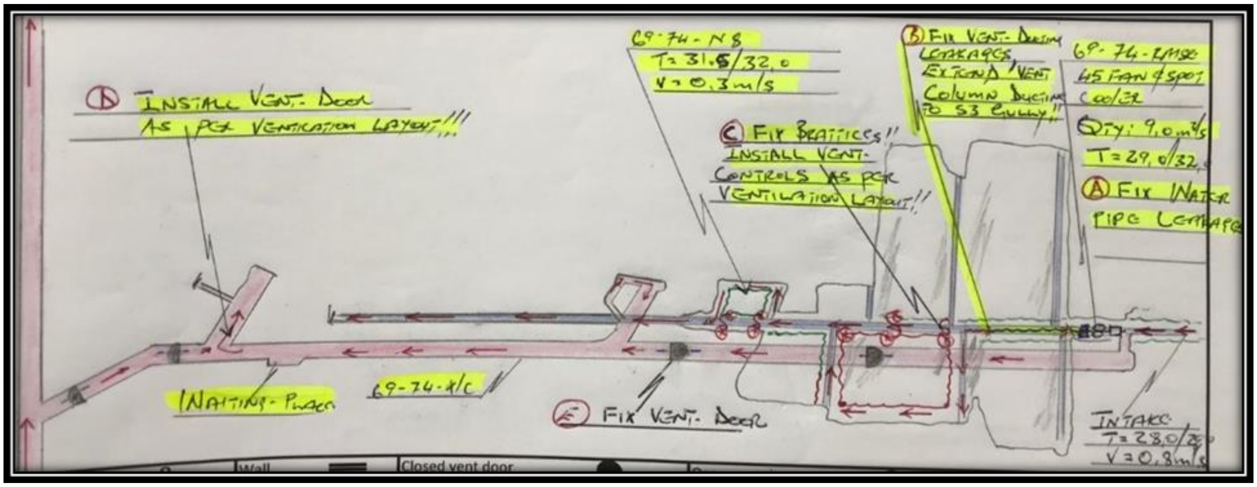

Figure 4-11: Analysis of a ledging Stope Mine B

The above stope ventilation report reveals the following at different points A – E (Figure 4-11):

- A: There is the presence of a cooling car located in the cross cut (Point A of Figure 4-11) where the temperature is 29.0°C (wb). However, it is highlighted that the water columns feeding the cooling car are broken and hence the cooling car is nonoperational;
- B: At this point, temperatures are not measured which raises the challenge of having a full view of the stope conditions. There is a need for the ventilation leakages to be repaired, as it affects the efficiency of the instope ventilation system. Important too is the extension of the ventilation column;
- C: Necessary temperature measurements are not taken either at this point. ventilation brattices are to be fixed to ensure that the ventilation reaches the stope panel faces and is not lost into the back areas. Additional ventilation controls need to be installed to keep the temperatures below 32,5°C (wb). There is an increase in the stope temperature after the ventilation has serviced a couple of panels; stope temperatures increase from the initial 29°C (wb) to 31,5°C (wb) with the air velocity dropping to 0.3m/s. Undoubtedly, these working conditions can cause heat stress and are conducive to poor productivity and unsafe working conditions; and
- D: A ventilation door is to be installed as per the ventilation layout. The absence of this door is a concern and a direct cause of the low face velocities and high stope temperatures.

The stope conditions above are not safe for the employees to work in and to be productive. It is noted that insufficient temperature measurements were conducted during this stope visit. Hence, depriving the report of valuable ventilation data that would allow for a proper analysis of the stope conditions. This report, therefore, reveals the poor practice of management and workers in carrying out their duties.

Although the wet bulb temperatures in this report have not reached the upper legal limit of 32,5°C (wb). The +31°C (wb) temperature is a reason of concern, as the stope is still conducting ledging activities and as panel progress toward the stope boundary ventilation conditions will most likely deteriorate. Nonstandard conditions must be rectified i.e. the fixing of the broken chilled water column and the installation of ventilation controls. Stope conditions could worsen if the highlighted deficiencies are not solved.

4.2.2.4 Mine B - Diagram 3

Figure 4-12 displays a ledging stope whose temperatures were measured to around 29°C (wb) and no ventilation controls or brattices were employed. The intake ventilation in the cross cut is already at a temperature of 29°C (wb), which is above the recommended target of 28°C (wb), and without the use of a cooling car operating stope, temperatures will be well above those that support safe and efficient mining operations. The stope indicates poor ventilation controls resulting in air travelling up the centre raise at a velocity of 1.2m/s while the S1A panel (in Figure 4-12) is serviced with ventilation with a temperature of 30.5°C (wb) at a sparse velocity of 0.4m/s.

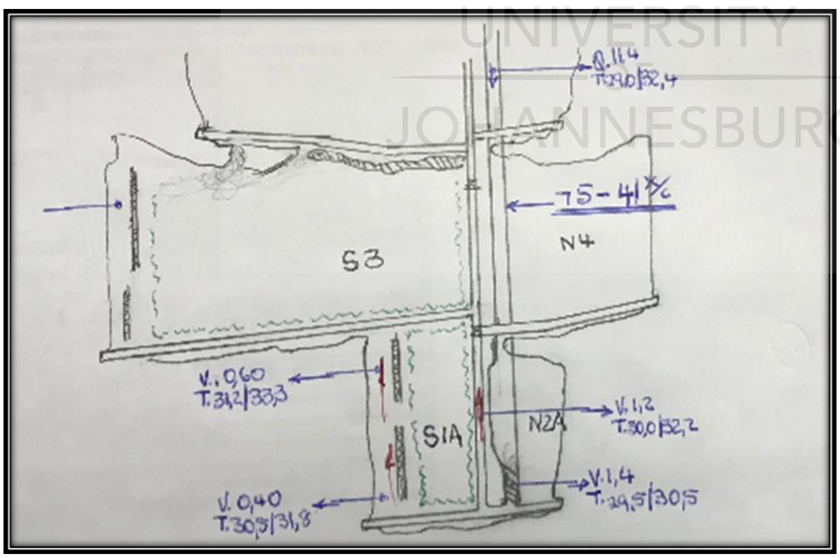

Figure 4-12: Analysis of ledging stope Mine B

Similar to other stopes with poor environmental conditions the stope faces (lead/lag of panels) are poor with long lead lags which promotes poor ventilation flow. The lack of ventilation brattices is a serious issue and is the reason for the low face velocities and high stope temperatures. The absence of these brattices impedes the cooled air from getting to the face. If ventilation brattices are not properly/efficiently installed ventilation will follow the path of least resistance and travel through the back areas of the stope – providing poor face conditions. The poor stope environmental issues are a result of the poor work practices by the employees.

It is essential for the installation of ventilation controls and brattices as shown in red on the above sketch. The last panel does not have any temperature measurements that have been taken. Which limits the ability of the report to present the proper view of the temperatures being experienced. Hence bringing out the challenge that this inadequate practice of reporting makes it difficult to create a safe environment for the workers.

4.2.3 Case Study: Mine C

This case study will analyse the reports received from the mine by analysing the diagrams, identifying the methods of cooling adapted, noting the underground temperatures experienced, etc.

4.2.3.1 General Description

Mine C is located in the Free State Province, some 270 km southwest of Johannesburg. Mining operations at Mine C comprise one primary underground mine, with a depth of approximately 2945m. While most of the ore extracted comes from mechanised mining (massive mining techniques), conventional stoping is still employed primarily to de-stress areas ahead of mechanised mining. Ore is processed at the plant adjacent to one shaft.

4.2.3.2 Mine C - Diagram 1

The ventilation report (Figure 4-13) highlights the efficacy of seven cooling cars operating a level of a mine. It shows that the area is cooled using seven cooling cars. The effectiveness of each one of them is as follows (from left to right Figure 4-13):

Cooling Car, No: N (V500v)

The cooling car (N) recorded intake air temperatures of 28.0°C (wb) and an outlet air temperature of 24.5°C (wb) resulting in a temperature reduction of 3.5°C (wb). The chilled water servicing the cooling car is 15.2°C (wb). Although the intake water temperature is above the target chilled water temperature of 12°C it can be seen that the cooling car is operating well, as the air temperature has reduced 3.5°C to an inflow air temperature to the stope of 24.5°C (wb).

Cooling Car, No: 6 (500v)

The cooling car (6) recorded intake air temperatures of 28°C (wb), and an outlet air temperature of 24.0°C (wb) resulting in a reduction of 4°C (wb). The chilled water servicing the cooling car is 15°C (wb). Although the intake water temperature is above the target chilled water temperature of 12°C, undoubtedly the cooling car is in good condition, as the air temperature has reduced by 4°C (wb).

Cooling Car, No: V (500v)

This cooling car (V) recorded intake air temperatures of 28.0°C (wb) and an outlet air temperature of 26.0°C (wb) resulting in a temperature reduction of 3.0°C (wb). The chilled water servicing the cooling car is 17.1°C (wb). Although it is evident that the intake water temperature is above 12°C. It can still be appreciated that the cooling car is efficient as the air temperature has reduced 3.0°C to an inflow air temperature to the stope of 26.0°C (wb).

Cooling Car, No: 4 (500v)

Intake air temperature 29.2°C (wb) and output temperature of 26°C (wb). A reduction of 3.2°C (wb). The chilled water servicing the cooling car is 13.5°C (wb), the temperature is close to the expected 12°C. With the low chilled water temperatures feeding the cooling car one would anticipate a lower reduction in the outlet air temperature i.e. closer to a drop of 4°C (wb). Encouraging is the fact that inlet chilled water temperatures close to the target of 12°C (wb) are achievable.

Cooling Car, No: 16 (500v)

The cooling car (16) recorded intake air temperatures of 28.0°C (wb) and an outlet air temperature of 24.5°C (wb) resulting in a temperature reduction of 3.5°C (wb). The chilled water servicing the cooling car is 16.2°C (wb). Although the intake water temperature is above the target chilled water temperature of 12°C it can be seen that the cooling car is operating well, as the air temperature has reduced 3.5°C to an inflow air temperature to the stope of 24.5°C (wb).

Cooling Car, No: 10 (500v)

Intake air temperature 28.0°C (wb) and output temperature of 27°C (wb). A reduction of 1.0°C (wb). The chilled water servicing the cooling car is 19.0°C (wb), the temperature is far from the expected 12°C. This cooling car is proving to be inefficient as a reduction of 1.0°C (wb) is considered to be too low. This could be a result of the intake water temperature that is above the target chilled water temperature of 12°C. It is also possible to assume that this cooling car requires servicing and maintenance.

Cooling Car, No: 8 (500v)

The cooling car (8) recorded an intake air temperature of 27.0°C (wb) and an output temperature of 25.0°C (wb). A reduction of 2.0°C (wb). The chilled water servicing the cooling car is 13.5°C (wb). Although the intake water temperature is close to the target chilled water temperature of 12°C. It is discouraging to note such a small reduction in temperature to an inflow air temperature to the stope of 25.0°C. Suggesting that the cooling car was not operating at its best.

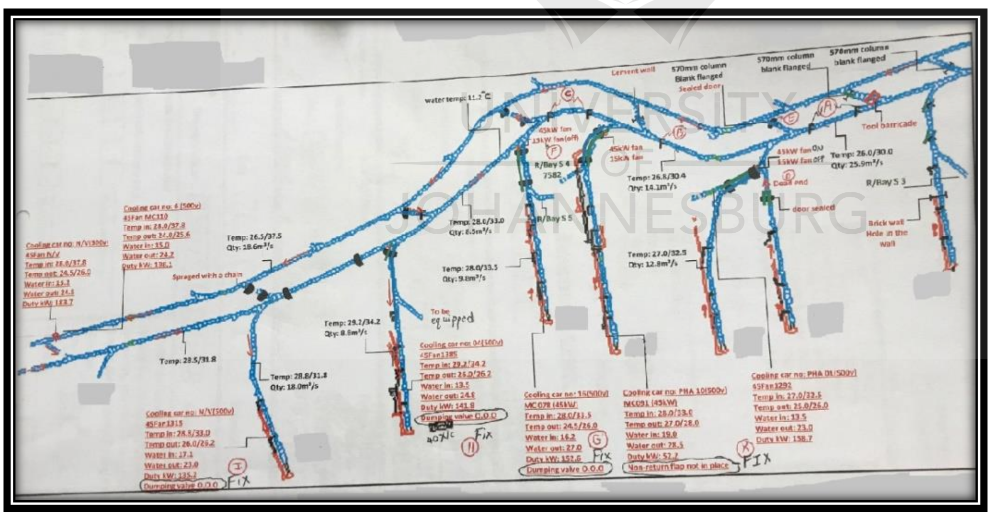

Figure 4-13: Analysis of Workplace Ventilation Mine C

After servicing the air, the above cooling cars make a general decrease in temperature between 1°C and 4°C (wb). This reveals that some of the cooling cars are not operating at their maximum capacity while others are operating efficiently. The chilled water supplying water to the cooling car is also not at the targeted temperature of 12°C (wb), with the chilled water temperatures reaching as high as 19°C (wb) on some occasions (Figure 4-13). It is recommended that isolation valves be opened about 1-hour before the start of working shifts to purge warm water from chilled water columns.

4.2.3.3 Mine C – Diagram 2

The stope ventilation report (Figure 4-14) highlights a number of issues.

- Point 2 has ventilation columns that are damaged and not connected. It is the responsibility of the production department to ensure that all systems are functioning properly to create a safe working environment;
- The efficacy of the cooling car at Point 3 is largely ineffective in that the temperature measured at the cross-cut is that of 30.5°C (wb). Unfortunately, at this point the intake temperature is unmeasured. Hence, it is challenging to carry out a proper analysis of the report; and
- Notably, at Point 5, the air compressor is opened but still, the face temperature close to Point 6 is recorded at 33.5°C (wb), raising the face conditions above the legal limit of 32.5°C (wb). Work is therefore expected to stop, and ventilation conditions fixed according to mine standards.

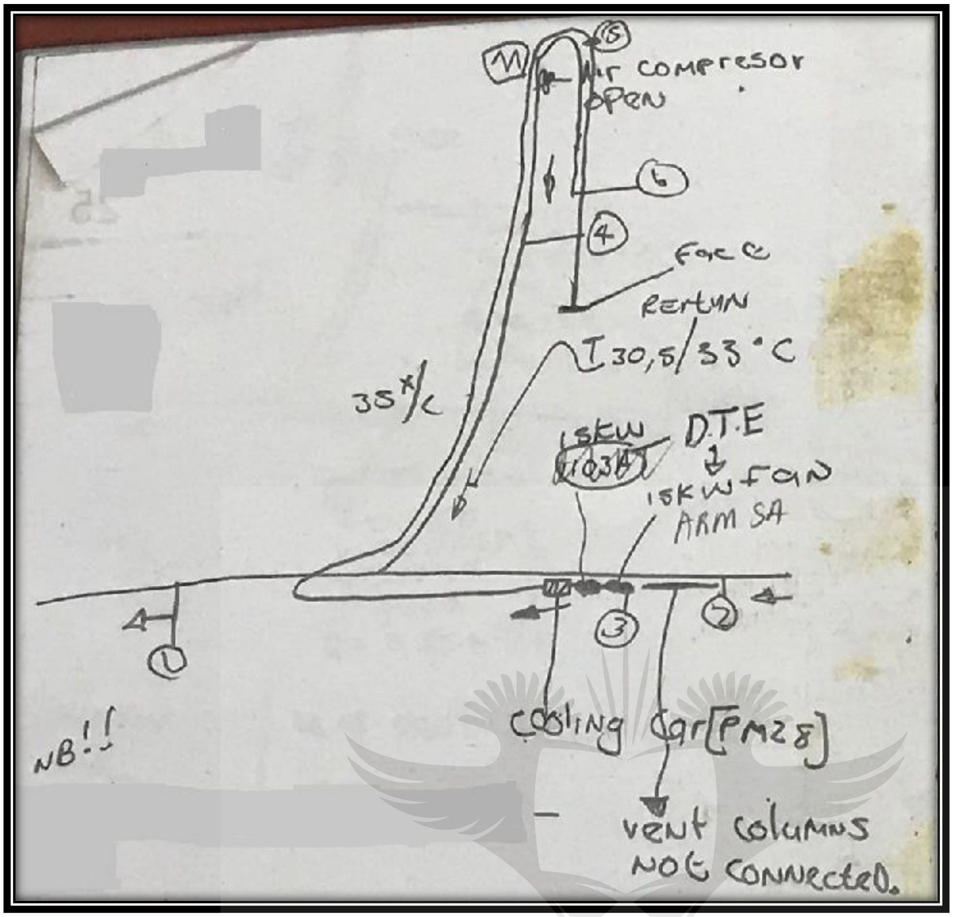

Figure 4-14: Analysis of a ventilation stope for Mine C

Figure 4-14 does not have enough temperature measurements, which makes it a challenge to understand and acquire accurate data that assists to improve the underground environmental working conditions. The above stope temperatures cause heat stress which reduces productivity and it also has a negative impact on the worker's health and safety. This manner of reporting does not depict the real situation of the underground conditions that the workers are exposed to, and therefore it is difficult for an adequate solution to be provided.

4.2.3.4 Mine C - Diagram 3

The stope ventilation report (Figure 4-15) highlights a number of issues.

- The effectiveness of the stope cooling system i.e. the cooling car in the cross cut is acceptable in that the intake air temperature is 29.0°C (wb) and the output temperature from the cooling car is 25.0°C (wb). A reduction of 4°C (wb) is very good and highlights the efficacy of the cooling car. The temperature of the chilled water servicing the cooling car is unknown as it is not measured;

- The stope air after servicing a couple of panels (see point X found in Figure 4-15) the stope air has increased from 28.5°C to 32.0°C (wb) at an unknown face velocity;
- By the time the air reaches the end of the last panel (Figure 4-15), the temperature reaches 33.0°C (wb) still with the velocity unknown at this point; and
- Critically, the wet bulb (wb) temperature has surpassed the legal limit of 32.5°C (wb) and is conducive to heat stress conditions and creates a working environment that is not suitable for good productivity nor supports a zero-harm environment.

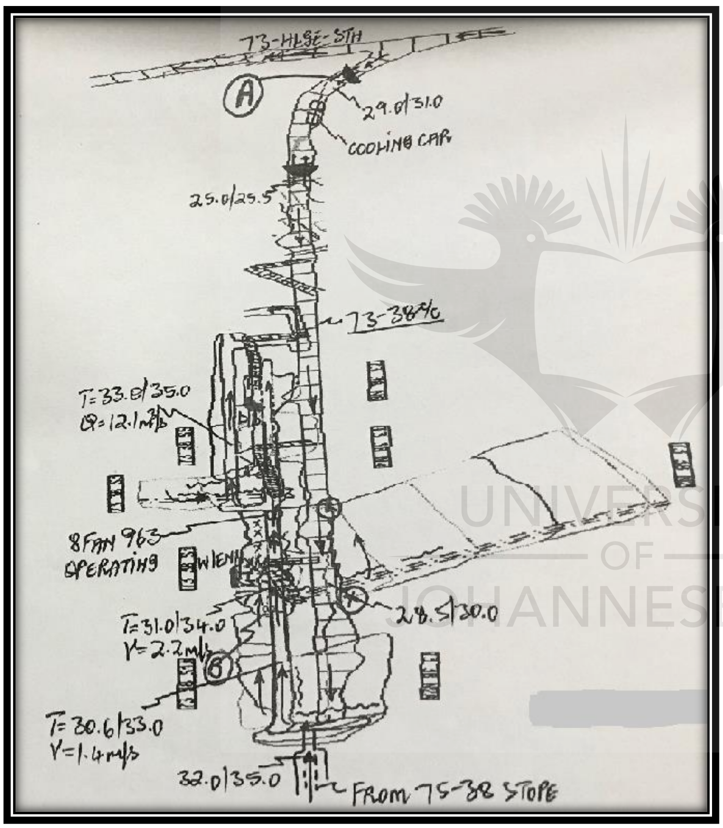

Figure 4-15: Analysis of a Ventilation stope Mine C

The above stope ventilation conditions are conducive to heat stress and heat stroke conditions. The ventilation report is insufficient in that it fails to measure velocity at all panels during the stope visit thus potentially excluding data. Further, it is essential to fix the cooling car to reduce the output temperatures. This kind of reporting is a hinderance to the goal of creating zero harm at the workplace.

4.2.4 Case Study: Mine D

Mine D case study ventilation reports that were obtained from the Mine were analysed so as to obtain a general view of the current underground environmental conditions that the workers are exposed to.

4.2.4.1 General Description

Mine D (Figure 1-4), which is located on the Gauteng-North West Province border, comprises twin vertical and twin sub-vertical shaft systems. Mining is undertaken using conventional mining methods in a sequential grid layout.

4.2.4.2 Mine D - Diagram 1

The stope ventilation report (Figure 4-16) highlights a number of issues.

- The effectiveness of the cooling cars is effective as the intake air temperature is 29.0°C (wb) and the output temperature from the cooling car is 26.0°C (wb). A reduction of 3°C (wb). The temperature of the chilled water servicing the cooling car is unmeasured, hence it doesn't provide sufficient data to make a complete analysis, however, based on the drop in the air temperature one can assume the chilled water to be reasonably chilled i.e. 15°C or 16°C (wb);
- The stope air after servicing one panel (Figure 4-16) has increased from 28.0°C to 30.5°C (wb) with a velocity of 2.7m/s;
- By the time the air reaches the end of the third panel (Figure 4-16), the temperature reaches 31.5°C (wb) with a face velocity of 0.5m/s, where an accident scene is recorded;
- Although the wet bulb temperature hasn't reached the legal limit of 32.5°C (wb) the temperatures are certainly very close to the upper limit and are certainly conducive to heat stress conditions and this creates a working environment that is not suitable for good productivity nor supports a zero harm environment. After the accident scene, the temperatures continue to rise to 32.0°C (wb); and
- The production department should ensure that the water for the cooling cars is opened fully and at all times as the employees tend to divert the use of the chilled water that is meant to service the stope.

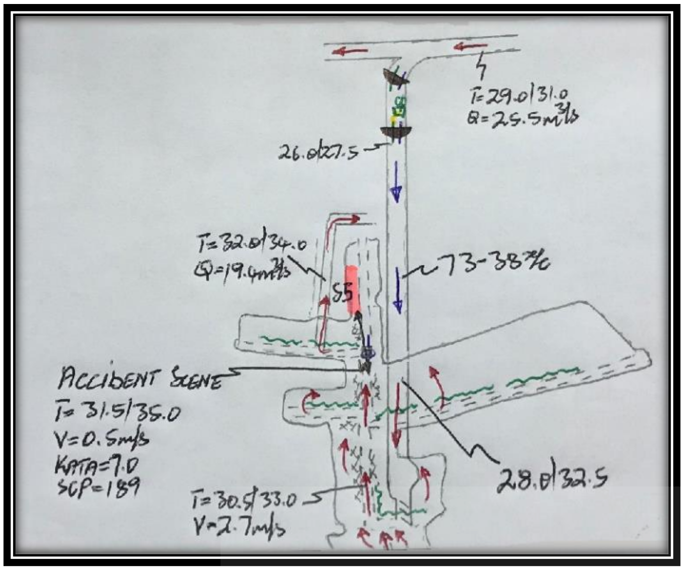

Figure 4-16: Analysis of a ledging stope Mine C

The input temperature of the chilled water is questionable as noted by the high stope temperatures. The above stope ventilation conditions are conducive to heat stress and perhaps even heat stroke conditions. The ventilation report is insufficient in that it fails to measure all panels during the stope visit thus potentially excluding data that may highlight temperatures in other panels that could be above 32.5°C (wb).

4.2.4.3 Mine D - Diagram 2

The stope ventilation report (Figure 4-17) highlights a number of issues.

- Notably, the stope is serviced by a cooling car and a fan that is not functioning properly (Figure 4-17). Their failure has caused the stope temperatures to rise above the legal limits of 32.5°C (wb).
- The intake air temperature to the fan is 32.7°C (wb) and the output temperature of 32.8°C (wb). An increase of 0.1°C (wb). This is a stope without a top entrance i.e. which means if the fan is out of order blasting fumes or poor ventilation conditions may exist. This is a dangerous situation that could result in a fatality, it is criminal and far from best practice. The ventilation conditions, as well as the ventilation layout, is far from best practice.
- The opened ventilation doors are a concern and have a material effect on the high stope temperatures.
- There is a need for a stope cooler to be installed at "A" from the recorded temperature of 32.2°C (wb).

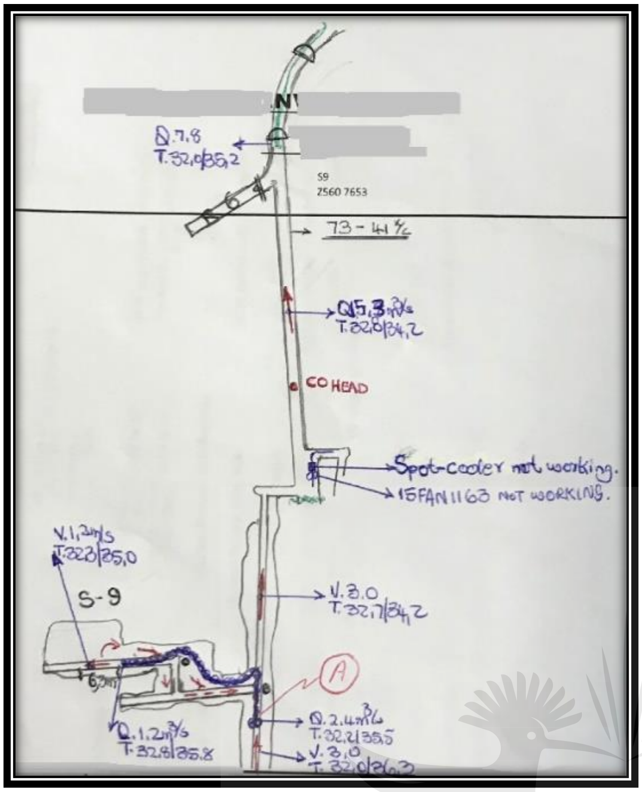

Figure 4-17: Analysis of the temperatures experienced in a hot stope

The high temperatures recorded in Figure 4-17 of 32,8°C (wb) are unsafe for the workers' health as they subject the workers to heat stress. No work should be conducted if the workplace environmental conditions are substandard. It is therefore critical to carry out daily checks and ensure that the fans are running and that the cooling car is functioning also that the running water is kept open at all times.

4.3 Summary of points noted in the ventilation reports

The cooling cars are supplied with chilled water that is above the targeted temperature of 12°C (wb), hence their effectiveness is reduced. It is recommended that chilled water be supplied as cold as is practically possible, say 12°C, in order to minimise air cooler requirements. The added benefit of the colder supply of water is that it promotes more compact air coolers and reduced air cooler water usage. The goal of cooling cars should be to achieve a reject temperature of 27.5°C (wb). Many stope reports reject temperatures of 30°C (wb) or more, which is not conducive to a productive environment nor does it support the industry call for 'zero harm'. Modelling work has shown that air temperatures can rise to 35°C (wb) in an uncooled environment compared to an average temperature of 25°C (wb) in a cooled environment. The above ventilation reports provide a general trend of the following:

- The efficacy of the cooling cars is questioned due to the small differences between the intake air temperature and the output temperature;
- Servicing a stope with a fan is not best practice as if the fan is out of order either the stope will receive inefficient volumes of air or stope workers will be forced to open the ventilation door and negatively affect other operating stopes;
- In-stope air coolers should be installed in every panel, excluding the 1st and 2nd panels, and should have a nominal duty of about 60kW;
- Ventilation air entering the stope should be pre-cooled to as low a temperature as practical, say 20°C (wb), to limit the need for in-stope cooling. Designs should be based on maximum in-panel air temperatures and not on average conditions;
- For deep stopes, to achieve face air velocities of at least 1m/s it will be essential that backfill in conjunction with well-maintained ventilation controls in the dip gully are provided. An acceptable and practical way to achieve this is to use double brattice curtains in the dip gully scraper path, installed adjacent to each panel, and leaving the travelling way open. To limit dust liberation a maximum face velocity of 2,5m/s is suggested (equivalent to a nominal face velocity of about 1,5m/s). To ensure adequate air quantities in the face zone it will be necessary to limit the minimum face to fill distance to 3 m which is consistent with observed current mining practice;
- It is necessary for daily checks on fans and in-stope coolers to be carried out to ensure that all ventilation systems are running at optimum;
- The ventilation department should make measurements in all panels. Insufficient data is measured in the stopes which is necessary to provide the Mine Supervisor with a full view of the stope environmental conditions; and
- Although in some stopes the wet bulb temperature hasn't reached the legal limit of 32.5°C (wb) it certainly is conducive to heat stress conditions and creates a working environment that is not suitable for good productivity nor supports a 'zero harm' environment.

This is evidence of the fact that more work is to be done if the stopes are to be kept safe for employees and if productivity is to be improved. Unfortunately, it is possible to assume that some temperatures are not measured so that substandard temperatures are not noted in the ventilation reports. This becomes a challenge as it is necessary to gather real-time data to provide solutions to substandard working environments. Having miners working in environments above 30°C (wb) temperatures is questionable.

It is appropriate to conclude that the current legal standards should be reviewed as the current limit of 32.5°C (wb) no longer reflects current safety requirements.

4.4 Analysis of the Extension Project

Mine D carries out an extension project that adds value to this study. The following section will analyse the relevant ventilation aspects of this project. The extension would introduce five additional working levels.

4.4.1 Case Study: Mine D

Mine D is situated in the West Witwatersrand Basin and mines the Ventersdorp Contact Reef as its primary ore body. The mine comprises twin vertical and twin sub-vertical shaft systems and uses conventional mining methods in a sequential grid layout. Mining currently occurs up to -3440mbs (metre below surface) with the proposed extension increasing the mine depth to approximately -4000mbs. The extension would introduce five additional working levels, over 560m, extending to the -4000mbs.

Figure 4-18 below shows the mine development layout in isometric view. The layout comprises a twin decline access system, a material incline system, a chairlift incline, and five (5) levels. Access to the extension area is through the existing 113 Level and 109 Level.

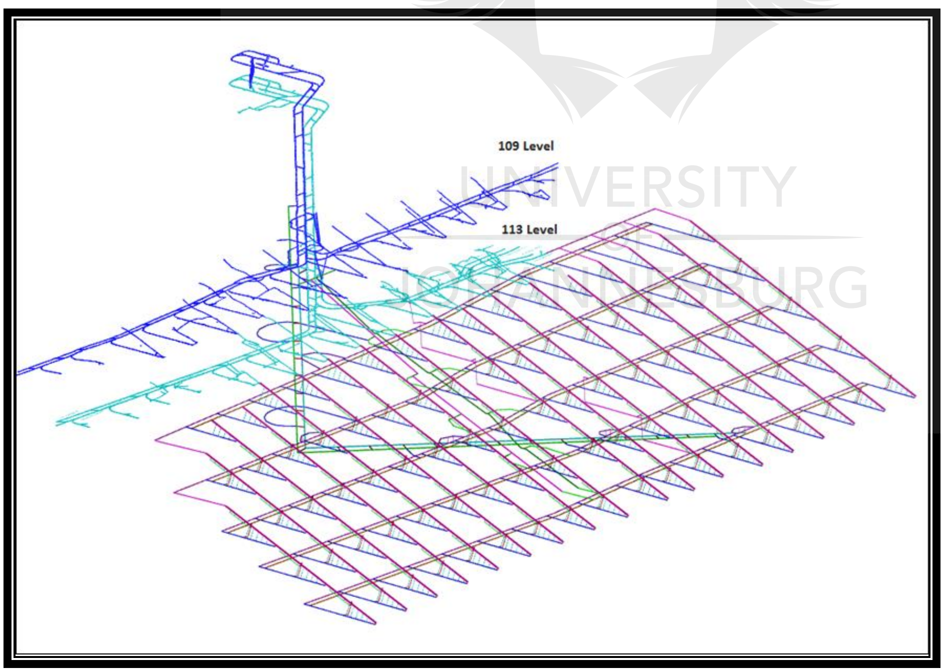

Figure 4-18: Deepening Project development layout (looking North East) (Harmony, 2018).

In order to reach the Deepening Project area, intake air, men and materials must travel down the Main Shaft (approximately 2.2 km deep) then another 1.0 km down the sub vertical shaft to 113 level. On reaching 113 level a further 2.5 km must be travelled before the main decline is reached. The total distance before reaching the Deepening Project area declines is some 5.7 km. The Main decline is approximately 3.5m long to reach the 127 level.

This puts considerable constraints on the system resistance for the air flow and this will require the installation of various booster fans. In addition, the heat pick-up from the excavations enroute will be considerable and will require extensive use of the existing cooling facilities on surface and underground.

The Deepening Project area (Figure 4-18) will be accessed by twin declines from 113 Level and extend to 127 Level. The initial level spacing (113 Level to 115 Level) is 60m vertically, thereafter the level spacing is 120m vertically.

The ability to concentrate and spatial perception decrease when the wet bulb temperature exceeds 28°C. Reaction times, on the other hand, remain fairly constant. Once the wet-bulb temperature rises above 29°C, individuals work faster, but less accurately, than they would below this temperature (Schutte & Franz, 2000). Using the above stated knowledge, it is therefore highly probable that temperatures VRT of 56.2°C will result in extremely hot working conditions which may lead to an unsafe working environment for the employees. Such conditions will most probably result in the occurrence of heat stress incidents. The various design criteria are given in the following tables.

Table 4-3: Depth and VRT 113 level to 127 level

Level	**Depth below surface**	**VRT °C**
113	3261 m	53.9°C
115	3321 m	54.5°C
119	3441 m	55.9°C
123	3561 m	57.2°C
127	3681 m	58.5°C

Table 4-4: Geothermal properties of the rock

VRT Equation	VRT = 0,011 (m)+18.0 °C
Density	3000 kg/m³
Thermal conductivity	5.0 W/m°C
Thermal diffusivity	2.1x10-6 m²/s
Specific heat	780 J/kg°C

(Harmony, 2018)

Table 4-5: Surface ambient design conditions

Summer design wet-bulb temperature	19 °C
Summer design dry-bulb temperature	26 °C
Summer design barometric pressure	87 kPa
Air density	1.0 kg/m³

(Harmony, 2018)

Sufficient intake airway capacity is required to facilitate acceptable environmental conditions, which has necessitated the use of four main intake airways of a large size (see Table 4-6). Failure to create this airway capacity will most likely result in high in-stope temperatures which may result in unsafe mining conditions and limit productivity.

Table 4-6: Intake airway sizes

ITEM	WIDTH	HEIGHT	AREA	VELOCITY	VOLUME m³/s
Main decline	6.0	4.0	24	8.0	192
Conveyor decline	6.0	4.0	24	4.0	96
Chairlift	4.0	4.0	16	6.0	96
IAW Mat Incline	4.0	4.0	16	10.0	160
				TOTAL VOLUME	544

(Harmony, 2018)

Table 4-7 shows primary and main shafts. A summer shaft station temperature on 109 Level was measured as 24.2/32.4°C. This was the temperature with the surface Bulk Air Cooler operating at only 3000kW. Figure 4-19 displays the ventilation and refrigeration schematic.

Table 4-7: Primary Shafts and Main Fans

Shaft	**Use**	**Diameter**	**Area**	**Air handled**	**Main Surface Fans**
Men & Materials	d/c	8.4 m	55.4 m²	1115 kg/s combined	
Rock/Ventilation	d/c	7.3 m	42.0 m²		
Sub vertical	d/c	10.0 m	72.5 m²	1115 kg/s combined	
Backfill Shaft	d/c	3.0 m	7.1 m²		
Main return	u/c	Bratticed	33.7 m²	915 kg/s	2 x 4.1 MW Fans operating Plus 1 x spare
Sub vertical	u/c	7.0 m	33.7 m²	915 kg/s	
Deelkraal	u/c			200 kg/s	1 x 2.2 MW fan operating Plus 1 spare

(Harmony, 2018)

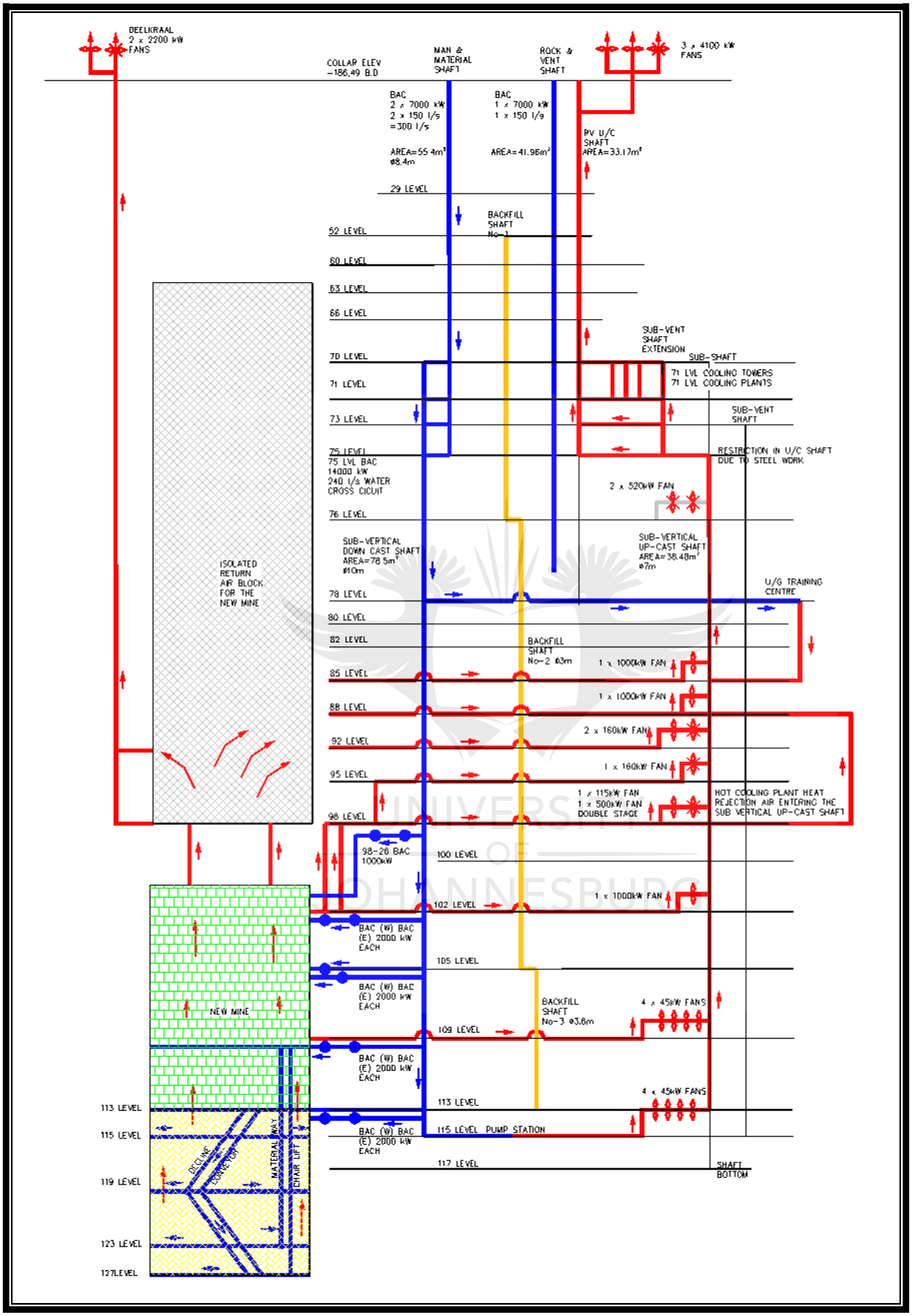

Figure 4-19: Ventilation and Refrigeration Schematic (Harmony, 2018).

The 1115 kg/s of intake air is more than sufficient for the mine. If the third main fan at Mine D is turned on, it only increases the air quantity by 150 kg/s and this is at the expense of running a 4100kW fan.

The deepened zone of the mine requires some 546 m^3/s at the point of use. This zone is at such a depth that adding more air increases the heat load of the mine due to autocompression, so there would be no advantage in attempting to add more air. The deepened zone should only have enough air to act as a means to remove pollutants and distribute cooling. Mine D has embarked on an extensive sealing programme to reduce ventilation leakage into worked out areas.

4.4.2 Cooling Currently Installed at Mine D

Mine D has several cooling installations. These are currently being refurbished as are the pumping arrangements and the various dams.

Below is a list of a summary of the original design specifications of these various systems and a realistic estimate of the potential output is also provided. The reason for this is that these systems have been installed for a considerable number of years and even if the refrigeration plants are "refurbished", in reality, the whole system never achieves its original design figures.

The following (Table 4-8) presents a summary of the realistic refurbished output and potential cooling available:

Table 4-8: Summary of the realistic refurbished output and potential cooling available.

Level	**Potential cooling (kW)**
Surface	31500
71	21,000
100	7000
Total	59500

(Harmony, 2018)

4.4.3 Production Stope Ventilation

Stopes are current positively ventilated using 1 x 45kW fan and 1 x 15kW fan forcing air through two 760mm columns above a set of ventilation doors in each cross cut. This ensures each stope is given a defined amount of air and helps overcome the changes in resistance of the stope during the production cycle. Some $15m^3/s$ of air are used per single-sided stope.

The cooling installations on 102 to 113 levels consist of 10 x 300kW cooling coils in a single structure on every half level. It has been advised that these coils are in good condition and are suitable for a clean and refurbishment and can be deployed in a cooling coil car and be placed in a positionally efficient manner as described below.

For a full production stope two 760mm columns each equipped with a 45kW axial fan connected to a 300kW cooling car to provide freshly cooled air into the relevant workings. A ledging or vamping stope will have a single cooling car and a production stope two cooling cars providing 600kW of cooling. The development cluster will be equipped with three cooling cars. Figure 4-20 displays a schematic diagram for a ventilation raise.

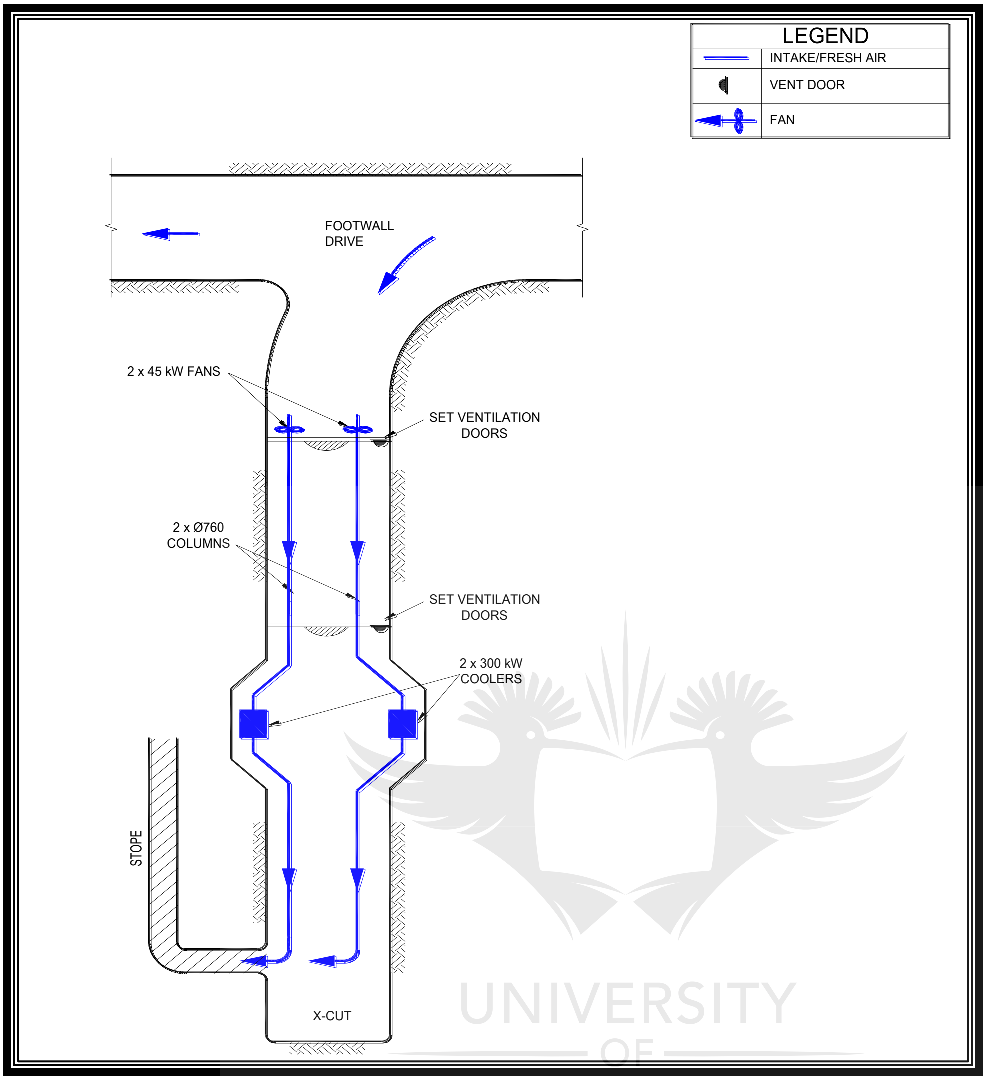

Figure 4-20: Schematic diagram for ventilation raise (Harmony, 2018).

To provide general cooling for the area, it is intended to move the 7000kW bulk air cooler on 100 Level from its current location to the intakes for the deepened zone

4.4.4 Booster Fans and Raise Bored Holes

Due to the high resistance of the ventilation system, each working end will have air forced into it, via a cooling car(s) to ensure adequate air is delivered to the working place. However, there will be a requirement for additional booster fans within the system. The position and size of these fans and raise bored hole/ventilation raises for both intake and return air will be determined using the Ventsim simulation.

4.4.5 Cooling, Refrigeration, and Service Water

The cooling, refrigeration, and service water system requirements have been integrated into the same system for Mine D Deepening Project.

Chilled water (cold <10°C) will be supplied to the 92 level energy recovery turbine which discharges into the chilled water dam on 95 level. This water will be a gravity feed system supplying the workings below 98 level and the extension project. The chilled water is reticulated from 95 level to the No 2 service shaft to 105 level, along 105 level to the No 3 service shaft. To service the deepening project refrigeration, the chilled water piping in the No 3 service shaft potentially needs to be increased to 400mm diameter. On 113 level, high pressure piping is routed to the Deepening Project service decline.

The design flow rate of the chilled water for refrigeration in the decline is 450l/s which requires a 450NB (Nominal Bore) high pressure pipeline. The chilled water system was a closed system. The schematic for the piping installation is shown in Figure 4-21. Chilled water is reticulated from the decline pipeline to cooling cars on each level. These pipelines are 200NB. The chilled water requirements per half level services the cooling cars for two raise lines stoping, one raise line development, vamping, and the development of the cross cut, haulage, and return airway. The chilled water supplies nine cooling cars operating at 6l/s each. The total flow has been calculated at 54l/s per half level or 108l/s for a level. A 200mm high pressure pipe will be installed from the material decline on each half level.

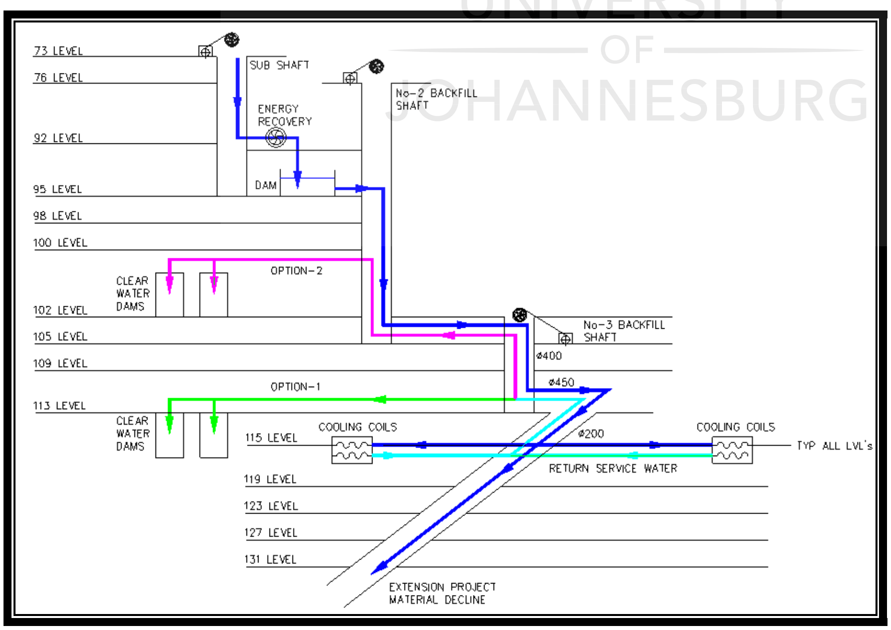

Figure 4-21: Chilled water piping installation (Harmony, 2018).

A portion of cooling car water discharge will be used as service water for the hydropower power packs during the production shift.

The service water for the mining operations based on the hydropower output capacity during the drilling shift for a half level has been calculated at 43l/s. The recycling system will reduce this to 22l/s, the balance of 21l/s will report to the foot wall as dirty water. Table 4-9 summarises the current cooling installations at Mine D.

Table 4-9: Current cooling installations

Location	Item	Design output (kW)	Quantity	System efficiency	Output (kW)
Surface	Refrigeration plants	42000	4 x 10500 kW units	75 %	31500
Surface	Chilled water	21000	250l/s @ 3°C down #	75 %	15750
Surface	BAC Shaft head	21000	Receiving new packing	75 %	15750
71 Level	Refrigeration plants	6 x 3500	Number subject to the actual availability of units	75 %	15750
71 Level	Refrigeration plants	2 x 7000		75 %	5250
75 Level	BAC	14000	Cools air going down the shaft	n/a	10500
100 Level	Refrigeration plants	3 X 3500	Only 2 units can operate at once	new	7000
100 Level	BAC	7000	Cools air going down the shaft	new	7000
102 Level	BAC 2 per lev	2 x 2350	10 x 300kW (nominal) coils in structure Each side 60 l/s	Incl. fan heat & losses	2700
105 Level	BAC 2 per lev	2 x 2350	10 x 300 kW (nominal) coils in structure Each side 60 l/s	Incl. fan heat & losses	2700
109 Level	BAC 2 per lev	2 x 2350	10 x 300 kW (nominal) coils in structure Each side 60l/s	Incl. fan heat & losses	2700
113 Level	BAC 2 per lev	2 x 2350	10 x 300kW (nominal) coils in structure Each side 60l/s	Incl. fan heat & losses	2700

(Harmony, 2018)

4.5 Chapter Summary

This chapter carried out a ventilation analysis of stoping conditions found on Mines A, B, C, and D that are operating in less than ideal conditions. From the gathered information It is evident that more work is to be done if the stopes are to be kept safe for employees and if productivity is to be improved. Unfortunately, it is possible to assume that some temperatures are not measured so that substandard temperatures are not noted in the ventilation reports. The chapter also studied the extension project at Mine D, analysing the ventilation systems that are required to introduce five additional working levels. The following chapter provides a conclusion to the study and recommendations for the way forward.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The overall aim of this research was to investigate current methods of cooling and ventilation. The resulting body of knowledge will allow mines to be safely and productively operated by means of improving underground working conditions. The specific research objectives were, to:

- Conduct an extensive bibliographical background research on underground mine ventilation and cooling;
- Evaluate the current underground in-stope temperatures and the cooling methods adapted to mitigate high stope temperatures using ventilation study reports for Mines A, B, C, and D; and
- Formulate recommendations and opinions of the standard environmental conditions acceptable for efficient working conditions as well as to protect the health and safety of underground workers and improve productivity.

This section visits the research objectives above, summarises the findings of this research work, and provides conclusions based on the findings. Importantly, the contribution of this research to the development of improved underground cooling will be clarified. Additionally, a section reflecting on the research process that has been undertaken is included. Recommendations for future research will be provided in terms of how to progress the research in ventilation and cooling. By adopting this structure, it is intended that the research work will be concluded to reflect on whether or not the objectives stated at the start of this dissertation have been met.

5.2 Research Objectives: Summary of Findings and Conclusions

The following were the objectives of the study and their outcomes:

5.2.1 Research Objective 1

Conduct an extensive bibliographical background research on underground mine ventilation and cooling.

Relevant data were reviewed through the revision of past journals, articles, and research work. Attention was placed on recent work with the aim of gathering information that is current and relevant. This objective has been well carried-out and the literature review provided a good foundation for the research study.

Using the knowledge gained from the literature review, the researcher analysed the cooling methods adopted at Mines A, B, C, and D. Atomisers, cooling cars, cooling garments, and fans, etc. are used to cool the workplace. The research also reveals the efficiency of these cooling systems, the advantages, and disadvantages of their use in the underground environment.

Due to the fact that the literature review was not only focused on the South African gold mines, it was also concluded that the cooling methods were not necessarily identical to all countries like Australia, German, etc. The reason for the differences was based on factors like cost, worker's compliance in adopting the cooling method, and management's effort to implement modern ventilation and methods.

5.2.2 Research Objective 2

Evaluate the current underground in-stope temperatures and the cooling methods adapted to mitigate high stope temperatures using ventilation study reports for Mines A, B, C, and D.

The literature review reveals that current South African legislation requires that no person shall work in a mine where the conditions are conducive to heat stroke, except if such work is carried out following an approved code of practice. In terms of a conservative but practical limit, thermal conditions 'conducive to heat stroke' exist, albeit only potentially so, whenever the wet-bulb temperature equals or exceeds 27, 5°C (Schutte, et al., 1994). The research also concluded that the thermal environment would have a negative impact on a worker's capacity to perform and coordinate movements in constrained space with speed and precision. Once the wet-bulb temperature rises above 29°C (wb), individuals work quicker but less precise than they would when operating below this temperature.

Literature also identified that selecting the most applicable method of cooling depends on the amount of heat that needs to be removed, the mining method used and economic constraints also suggesting that due to the high capital and operating costs of mine cooling systems, a trade-off of these systems should be conducted before selecting the optimum system. Mines implement ventilation and cooling systems and controls to make these areas secure for working. Artificial mine cooling systems are sometimes incorporated with the ventilation system when safe working conditions cannot be achieved by using ventilation only.

An advantage of in-stope cooling systems is their ability to provide cooling in localised areas, however, this requires infrastructure such as return airways or waterlines from the surface and these waterlines should be able to handle the increased water flow required for condenser cooling (Calizaya & Marks, 2011).

Analysis of the results indicates that the current methods highlighted as most common for cooling the underground environment were cooling cars, fans, and atomisers systems amongst others. As discussed in Chapter 3, all four mines have adopted the cooling of stopes using cooling cars positioned at the entrance to the stopes or directly inside the stope. For Mine A, the challenge with this cooling strategy was that although there was chilled water servicing the cooling cars, the workers often diverted its use. This had the disadvantage of limiting the full efficiency of the cooling car to cool the stope. The use of atomisers for the mine did not prove to be of great efficiency as the reduction of temperature was just 1-2°C (wb), and the effect of the atomiser was limited to the immediate area of the spray. Albeit the above, the atomiser could find use on the immediate face for hot stopes.

The major challenge at Mines A, B, C, and D, highlighted by the ventilation reports is that the cooling cars were often malfunctioning or switched off, resulting in the stope temperatures reaching or exceeding the legal limit. In practice, as evidenced in the case studies, some specialists are of the opinion that cooling cars have the challenge of being extremely energy intensive and often had their efficiency lowered by the chilled water servicing them (i.e. water too warm to provide sufficient cooling). The chilled water servicing the cooling cars generally arrived at the cross cut at a temperature of about 16°C - 20°C and sometimes, even more, resulting in poor cooling performance by the cooling cars. In some cases, the lack of ventilation brattices was also highlighted as a critical factor for poor in-stope conditions as the failure to install ventilation controls results in low face velocities and high stope temperatures. Ventilating back stopes with a fan has proven not to be best practice, as if the fan is out of order either the stope will receive inefficient volumes of air or stope workers will be forced to open the ventilation door, which negatively affects stopes operating beyond the cross cut. This method of ventilation does not support a zero harm working environment.

Mine D extension project would introduce five additional working levels. This puts considerable constraints on the system resistance for the air flow and this will require the installation of various booster fans. In addition, the heat pick-up from the excavations enroute will be considerable and will require extensive use of the existing cooling facilities on surface and underground.

Due to the high resistance of the ventilation system, each working end will have air forced into it, via a cooling car(s) to ensure adequate air is delivered to the working place. However, there will be a requirement for additional booster fans within the system. The position and size of these fans and raise bored hole/ventilation raises for both intake and return air will be determined using the Ventsim simulation.

Chilled water is reticulated from the decline pipeline to cooling cars on each level. The chilled water supplies nine cooling cars operating at 6l/s each. For a full production stope two 760mm columns each equipped with a 45kW axial fan connected to a 300kW cooling car to provide freshly cooled air into the relevant workings. A ledging or vamping stope will have a single cooling car and a production stope two cooling cars providing 600kW of cooling. The development cluster will be equipped with three cooling cars. The deepened zone should only have enough air to act as a means to remove pollutants and distribute cooling. Mine D has embarked on an extensive sealing programme to reduce ventilation leakage into worked out areas. Microclimate cooling systems are used to cool the area directly surrounding the mineworker; these systems, therefore, have positional efficiencies as high as 100%. In the interviews with the respondents, the frequent point has been that cooling vests have the disadvantages that they are bulky, and the cooling effect lasts between two to three hours before re-charging is required. These garments were said to be expensive for high production cost mines such as Mine A. It was also suggested that the workers would neither be keen to have the additional weight of the cooling garment, as they already have to carry the rescue pack, helmet, cap lamp, etc. as part of their underground kit.

This study has also revealed that cooling rooms, which are small-sized rooms developed underground close to the working areas are uncommon in the South African gold mines. The challenge with cooling rooms is related to their construction and maintenance. In the case studies, the management was of the opinion that any cooling method that relied on the workers to be implemented often did not end with good results. They suggested that it was often not easy to get the workers to cooperate and comply with the implementation of any new method.

5.2.3 Research Objective 3

Formulate recommendations and opinions of the standard environmental conditions acceptable for efficient working conditions as well as to protect the health and safety of underground workers and improve productivity.

Mining is inherently a high-risk industry, particularly when considering the deep-level underground hard rock mines. OHS (Occupation Health and Safety) of mine personnel plays an important role in this regard. The role of the OHS Management systems is to contribute to the protection of personnel from hazards and the elimination of work-related injuries, illness, diseases, incidents, and death. Minimising the negative health effects of exposure to hazards is the principal motivation for the evaluation and control of exposure.

Schutte *et al*. (1994) highlighted that heat increase above 29°C (wb) can negatively affect safety and productivity because of physiological effects such as loss of concentration and errors of judgement. As such, Schutte *et al*. advised on the importance of maintaining a core body temperature within narrow limits of around 37°C to prevent brain dysfunction. In the study, carried out by Le Roux in 1990 he found that workers can perform at 100% production capacity at 25°C (wb) but drops at 32°C - 33°C (wb) (Figure 2-3). As early as the 1950s, studies conducted indicated a decrease in performance for both the physical and cognitive tasks when the thermal environment was above 27°C (wb) and 32°C (db).

These studies combined with experience have led to the development of guidelines for the compilation of Mandatory Codes of Practice aimed at assisting employers in compiling their COP specific to their operations.

From the results of this study, inarguably most mines will be more content with the maximum legal limit at 32.5°C (wb) because the cooler they have to make the stope the more expenses they have to consider. On the contrary, some ventilation specialists thought that this limit has become outdated to the 21st century mine worker, which includes women in mining. Conclusively, such major issues are being pushed under the carpet at the risk of workers' health and safety.

The aim to bring down the temperature limit to 28°C (wb), which was targeted for this research was considered to be over ambitious by some respondents. For example, Mine A aimed at just reducing the temperature below 28°C but also highlighting the expense that comes with achieving this goal as too great for the mine to implement.

The ventilation reports have shown otherwise; temperatures can almost reach the legal limit in the presence of cooling cars that need repairs. The evidence of the poor reporting, where the ventilation reports exclude data that reveals the temperatures for a complete analysis, shows that the reporting standards for the underground environment require improvement to better the overall stope environment, increase productivity and promote zero harm for mine workers.

5.3 Limitations and Strengths

There are limitations to this research, as well as issues related to the fact that the results of this study cannot be generalised to the wider underground ventilation research community. Indeed, the results of this research cannot even be generalised to represent all deep gold mines: although key experienced staff were interviewed, and strategic documentation referred to.

The issue of depending on interviews as the main source of data, when interviewees can exhibit bias or poor memory recall, was dealt with by ensuring that the researcher was not depending on just, interviews, but also data received from past ventilation reports.

Several views were collected on the same issues, from directors and managers, etc, ensuring that the researcher was not dependent on one or two respondents for key data. Second, staff/juniors who have more opportunities of going underground were also interviewed, further removing the dependence on opinions that may be factually wrong or skewed and to place academic staff views in a wider context, lessening the opportunity for bias or misinformation.

To organise an interview, with specialists, can be a challenge as they are often very time conscious and if they eventually allow you to meet them, they can at times be willing to give limited time. However, such a scenario brings with it problems that, if not managed properly, may hinder the research.

After the transcription of interviews, Mine names were replaced by codes (Mine A, Mine B, Ventilation Engineer for Mine A, and so on); and a deliberate and significant time-gap created between the transcriptions and transcription analysis to further minimise the possibility of bias when interpreting interviewee's opinions. Table 5-1 is a summary of the strengths and limitations of the research.

Table 5-1: Strengths and limitations of Quantitative Research

Advantages of quantitative research	**Limitations of quantitative research**
The interviews were not just fixed to Mine specialists but also spread to Consultancies and consulting engineers.	Does not provide comprehensive information about human experience or perceptions due to the use of a structured questionnaire enabling participants to express their private views.
Another researcher may obtain similar results using the same method.	Interviewees were recorded which could have made them hesitant to give an honest opinion.
This study enabled the use of structured interviews but also with open end questions. Hence, more information was obtained.	

5.4 Guideline for Deep and Ultra-deep Operations

The following section provides a guide on the way forward for deep level mining. Bringing to light possible solutions on the challenges experienced in the underground mine, based on the experiences of specialists and past research carried out.

- Challenging the 32.5°C limit

As early as the 1950s, studies conducted indicated a decrease in performance for both the physical and cognitive tasks when the thermal environment was above 27°C wet-bulb and 32°C dry-bulb. Schutte et al. (1994) highlighted that heat increase above 29°C (wb) can negatively affect safety and productivity because of physiological effects such as loss of concentration and errors of judgement. As such, Schutte et al. advised on the importance of maintaining a core body temperature within narrow limits of around 37°C to prevent brain dysfunction. In the study, carried out by Le Roux in 1990 he found that workers can perform at 100% production capacity at 25°C wet-bulb temperature but drops at 32°C - 33°C wet-bulb temperatures. These studies combined with experience have led to the development of guidelines for the compilation of Mandatory Codes of Practice aimed at assisting employers in compiling their COP specific to their operations.

From the results of this study, inarguably most Mines will be more content with the maximum legal limit at 32.5°C (wb) because the cooler they have to make the stope the more expenses they have to consider. A shortfall to the South African heat stress management system is that it is based on temperature limits that were established many years before there were any female workers in the stopes thus, in the opinion of some of the interviewers, current regulations do not take into account the heat tolerance levels for women. It is highly recommendable that research further investigates these heat stress management standards and governmental regulations. Further research is required to fully understand how environmental conditions impact on the 21st century worker, as well as specifically women working in hot underground environments. The current legal standards should be reviewed as the current limit of 32.5°C (wb) no longer reflects current safety requirements and is out of sync with other international standards; noting that South Africa gold and platinum mines, unlike other international countries, conduct a labour intensive mining method in narrow vein conditions. In any workplace in an underground mine, and any tunnel under a surge stockpile on the surface of a mine, the manager of the mine must safeguard that: if the wet bulb temperature surpasses 25°C (wb), an air velocity of not less than 0,5m/s is provided (New South Wales Government, 2014). Conclusively, such major issues are being pushed under the carpet at the risk of workers' health and safety.

- Cooling garments

Cooling garments are not common in the South African mining industry and are thought to be expensive. The most ideal cooling garments must offer the wearer a high degree of mobility, lightweight, and an extended cooling duration. Research on body-cooling garments that use different technologies to cool the wearer's microclimate and prevent the rise in internal temperatures has identified a multitude of cooling garments categorised as active and passive cooling garments.

It is recommended that further research and modification into the applicability of the Evaporative and Thermoelectric cooling garments be considered. Further research will be required to assess the applicability of these garments in underground mining and will involve the understanding of the following parameters:

- The effectiveness of the garment, considering the typical stope temperatures and relative humidity levels,
- The average metabolic rate of an underground worker, particularly of those who work at the face area,
- The garment cooling capacity based on the expected metabolic rate of the worker,
- The weight of the garment,
- The mobility requirement of the wearer, and
- The comfortability of the garment.

The evaporative cooling garment is already available in the market and only requires modifications and assessments based on the above parameters. The thermoelectric garment, on the other hand, is still in the prototype stages and it will also require further research and development based on the above parameters.

Although cooling garments are at times considered to be impractical for various reasons such as cost, weight, mobility, etc., the use of cooling garments can be ideal under conditions where a worker is feeling unwell, fatigued, dehydrated, or has over-consumed alcohol (i.e. returning from a long weekend or pay weekend). In these instances, the worker may not feel completely fit but would have presented themselves to work. In these cases, the worker may benefit from the use of cooling garments, especially where an individual is to work in a hot working environment (>29°C (wb)). In certain circumstances, ventilation controls might not be effective enough, and body-cooling garments can be used to regulate the worker's microclimate by reducing their core body temperature.

- Cooling Cars and Spot Coolers

Spot cooling of air can be done at the entrance to the stopes or directly inside the stope. Cooling of the air at stope entrances is required when the air flow through the mine is not enough and thus requirements for the recirculation of air are necessitated. This type of cooling is preferred to cooling inside the stope because it is more practical to implement and it is more economical. Furthermore, cooling of the air at the entrance requires less refrigeration capacity than bulk air coolers that are affected by air leakages and temperature.

Spot coolers have a capacity that ranges between 70kW and 350kW. Heat is normally rejected to the mine service water at temperatures of between 35°C and 45°C. Insulated piping helps to prevent the heat from contacting intake airflows. The service water flow rate varies depending on the temperature but, it is about 0.02L/s per kW of cooling at 21°C water temperature.

Leakages if not managed can generate humidity in the crosscuts and haulages and potential mud rushes in stopes and orepasses. In-stope cooling also requires further research and manufacturing of more mobile units to operate within a stope.

Air cooler should be kept as close to the face as possible and for convenience should be relocated at the same time that the face scraper winch is moved forward (typically every 40 m face advance). Air coolers should be sized and fitted with skids to facilitate manhandling within stopes.

Spot coolers are heavy and difficult to move hence they should be manufactured in such a way that allows for easy instalment and maneuverability. It is also essential for them to be serviced and to undergo maintenance regularly.

The following are some of the recommendations for in-stope cooling based on the Deepmine Project (Butterworth & Ramsden, 2002):

  - Water usage should be between 0.8t/t and 1.5t/t
  - The wet bulb temperature of stope intake air should be about 28°C to reduce in-stope cooling requirements.
  - Pre-cooling of stope intake air should be conducted close to the stope entrances.
  - Water usage in stopes should be controlled; leaks and the discharge of chilled water onto rock surfaces should be avoided.
  - In-stope air coolers should be in operation an hour before a shift starts until the end of the shift.
  - In-stope coolers should have a nominal duty of 60kW.
  - An air velocity of 1 m/s should be on the stope face for adequate air cooling power.

- In operations that use backfill, it should be cooled to 25°C or less so that it does not add to the heat load at the stope.
- Chilled water to air coolers should be provided 1 hour prior to the start of the working shift.

The efficiency of a spot cooler can be improved by designing it with a closed loop water cycle to avoid the evaporation of water and increase which leads to humidity downstream from the stope.

Recommendations for research and development to design and develop an in-stope cooler that is light, portable, affordable, and compatible with the cooling necessities of a mine. Moving the in-stope cooler from one panel to the next ought not to hinder the production schedules. Spot coolers can be effective if the correct engineering practices are followed, additionally, consistent maintenance services from the manufactures should be considered and not be given to the workers as their responsibility to achieve the best efficiency output of these cooling systems i.e. the service providers should be contracted outside of the mine.

It is recommended that chilled water be supplied to the stope as cold as is practically possible, with 12°C, being recommended in order to minimise in-stope air cooler requirements. The added benefit of the colder supply of water is that it promotes more compact in-stope air coolers and reduced air cooler water usage.

It is recommended that national research programmes, such as SAMERDI should investigate the manufacture of in-stope spot coolers to meet the need of the industry. Further, manufacturers of cooling cars should look to modify the cooling cars to be less demanding of maintenance and move towards real-time monitoring of all cooling cars.

To avoid hot stope conditions at the start of working shifts, it is necessary to operate cooling cars air coolers continuously. In–stope air coolers should ideally be operated from 1-hour before workers enter the stope at the start of the shift up to the end of the shift. Again, the use of 4IR technology should be used to facilitate the remote management of all cooling systems.

- Cooler Water and Air requirements

In a stope, the air-water ratio is also limited by available face air quantity. The use of higher airflow rates will result in the recirculation of cold air and will severely reduce air cooler performance. The minimum face air quantity is 4.5m^3/s (3m x 1.5m x 1m/s). However, in practice this air quantity could vary between panels and for different stopes and a safety margin of 20% should be introduced when considering air cooler design. Therefore, an airflow rate of 3.6m^3/s (4.5m^3/s x 0.8) is proposed for air coolers. This yields an air-water ratio of 4.3 (6.4kg/s/1.5l/s) at 5000m depth and 3.5 at 3000m. The air-water ratio increases with depth due to air density dependence. These air-water ratios are considered appropriate (Calizaya & Marks, 2011)

- Cooling rooms, rest periods, work cycles.

The use of cooling rooms has not been well researched, nor reported. For some mines, they consider cooling rooms to be a challenge to productivity, as management views it as an alternative for workers to hide and stay for longer periods in those cooler rooms. Rest periods have also been viewed negatively because they would require "…discipline and maturity…" from the workers in order for rest periods and rest rooms to be implemented. The two concerns would require further research as very little literature has been found regarding rest periods and cooling rooms. The Canadians use environmental temperatures to guide the work duration between breaks.

The South African mining industry has not conducted sufficient research in the use of cooling rooms, hence it is recommendable for further research to be carried out on the subject.

- Drinking water

This, along with the poor hydration status of workers at the start of and during the shift indicates that education at all levels (workers, supervisors, management) about the need to report to work well-hydrated, and then to drink sufficient fluids during the shift (including the provision of palatable, potable water on the job), would substantially reduce heat illness in mine workers. Providing readily accessible cool drinking water (12°C–15°C) and encouraging all employees to drink a cup of water every 15 to 20 minutes is recommended to prevent heat stress. Hydration is not the only risk factor in developing heat illness; nor should the management of hydration be used in place of maintaining adequate environmental conditions in the workplace or reducing the physical work rate where practical. It is, therefore, necessary to investigate the effect of shift work and sleep-related fatigue on sleep patterns and, subsequently, on health and safety.

- Taking measurements

It is essential that full measuring of the stope is carried out so that management could get a full picture of the entire stope at one time - not just a snap shot of one or two panels.

The evidence of the poor reporting, where the ventilation reports exclude data that reveals the temperatures for a complete analysis, shows that the reporting standards for the underground environment require improvement to better the overall stope environment, increase productivity and promote zero harm for mine workers.

- Maintenance and training

Monitoring combined with maintaining and improving the current ventilation infrastructure will promote alleviating problems associated with heat disorders. This will involve employing well-trained people to conduct maintenance while following the best maintenance practices. Maintenance of spot coolers and poor ventilation controls which equates to 30 to 50 percent air leakages.

The ultimate effect of reducing underground temperatures and improving the general environment is the improved OHS and improved productivity of underground workers. With the increasing issues of health being raised, workers must be trained and educated so that they can understand the risks.

- Focusing Chilled air and Backfill

Other factors also need attention like focusing the chilled air to the work face as that is where the workers would need it most. Currently, ventilation controls are poor. Backfill can be used as one method to improve ventilation controls and diminish the impact of heat being sourced from the exposed rock faces.

- Ventilation on Demand

In order to control escalating running costs, mine operators need to find ways to reduce electricity usage. Many current ventilation systems are very wasteful as they constantly ventilate the entire mine, including areas that are not being worked. The best solution to this problem is the implementation of a Ventilation on Demand (VOD) system.

Ventilation on demand will facilitate the ability to direct ventilation air in an underground mine to the area that requires it, at the quantity need for the local activities at the time. Requires fan and louvers controls, sensors to measure workplace environment, "tags" to identify where equipment is operating, and a computer control to manage air flow.

5.5 Conclusions

The main conclusion that can be drawn from this research on ventilation is that there are challenges that will come with any selected cooling method for example cost, maintenance, efficiency, etc. This research has shown the need for mine's operating under >29°C (wb) temperature to adapt to a cooling system that best suits the mine, its operating conditions i.e. LOM, availability to capital, etc. Many systems have been used in conjunction with one another in an attempt to provide for the cooling effect required. Many potential barriers can impede the 100% efficiency of some of the systems, such as maintenance and the workers accepting the system being implemented. However, the lesson of this research work is that ventilation and cooling ought not to be viewed as non-urgent. Health and Safety might not have been given a priority in past research work but due to factors like heat illness, increased rate of accident, and decrease in productivity it should be further investigated. In simple terms, more research work is required in underground mines to promote a zero harm environment for both men and women, as well as promote a working environment conducive to conformant mining activities and increased worker productivity.

The above research leads to the conclusion that, in general, performance and productivity for moderate work decrease as the ET or CET exceed 30°C (wb) to 28°C (wb). Temperatures below 27.5°C (wb) are suitable for hard work. As most work in a narrow tabular mine should be classified as hard work, the in-stope temperature target should be less than 28°C (wb).

One is not generalising that what was concluded in this research automatically applies to all gold mines moreso it is expected that the results of this research will be representative of mines experiencing a hot working environment. Instead, this research is appealing to the concept of relatability: that what was researched in this study will be of interest to other researchers and the mining industry as a whole. The contribution of this research work to the ventilation knowledge pool will be developed from a synthesis of case studies analysis, data received from Mines (A, B, C, and D), and the findings of the literature review.

It is however expected that, in the fullness of time, as more case studies are implemented by other researchers, the contribution to the ventilation challenges will be gradually overcome and developed accordingly.

5.6 Recommendations

Elevated temperatures will remain a major hazard to underground personnel as mining progresses deeper and further from the shaft. The legislative framework that has been laid for the mining industry seems to suffice to keep the workers safe. It is important to note that the legislative framework is only as good as the mining operations that implement it. The temperature limits that have been proposed were based on data that was collected many years back and involved only male workers. In the past decade, the industry has seen the increased participation of women in mining, particularly in underground operations. This gives rise to the question of whether these limits are still relevant considering the participation of women and the industry wide goal of zero harm.

Monitoring combined with maintaining and improving the current ventilation infrastructure will promote alleviating problems associated with heat disorders. This will involve employing well-trained people to conduct maintenance while following the best maintenance practices. The ultimate effect of reducing underground temperatures and improving the general environment is the improved OHS and improved productivity of underground workers.

It is recommended that mines follow a systematic approach (as pointed out below) in determining ventilation and cooling strategies in order to achieve acceptable underground environmental conditions.

- the insulation of pipes to promote 12°C (wb) intake water;
- focus on water leakages;
- maintenance of spot coolers and poor ventilation controls which equates to 30% to 50% air leakages; and
- Whilst the use of nets on the face can be used for safety they can also have lights and atomisers incorporated into them so that when one is working, a mist of chilled water at 4°C can be descending from the hanging thereby producing a cooling effect.

5.6.1 Cooling garments are at times considered to be impractical for various reasons such as cost, weight, mobility, etc. under what conditions can the use of cooling garments be ideal for the worker?

Cooling garments are not common in the South African mining industry and are thought to be expensive. The most ideal cooling garments must offer the wearer a high degree of mobility, lightweight, and an extended cooling duration. Research on body-cooling garments that use different technologies to cool the wearer's microclimate and prevent the rise in internal temperatures has identified a multitude of cooling garments categorised as active and passive cooling garments.

Further research will be required to assess the applicability of these garments in underground mining and will involve the understanding of the following parameters:

- The effectiveness of the garment, considering the typical stope temperatures and relative humidity levels;
- The average metabolic rate of an underground worker, particularly of those who work at the face area;
- The garment cooling capacity based on the expected metabolic rate of the worker;
- The weight of the garment;

- The mobility requirement of the wearer; and
- The comfortability of the garment.

The evaporative cooling garment is already available in the market and only requires modifications and assessments based on the above parameters. The thermoelectric garment, on the other hand, is still in the prototype stages and it will also require further research and development based on the above parameters.

Although cooling garments are at times considered to be impractical for various reasons such as cost, weight, mobility, etc., the use of cooling garments can be ideal under conditions where a worker is feeling unwell, fatigued, dehydrated, or has over-consumed alcohol (i.e. returning from a long weekend or pay weekend). In these instances, the worker may not feel completely fit but would have presented themselves to work. With such considerations, the worker may benefit from the use of cooling garments, especially where an individual is to work in a hot working environment (>29°C (wb)). In certain circumstances, ventilation controls might not be effective enough, and body-cooling garments can be used to regulate the worker's microclimate by reducing their core body temperature.

5.6.2 In-stope cooling systems should be implemented to supplement a mine's existing ventilation and refrigeration system what are the recommendations for in-stope spot coolers?

Spot cooling of air can be done at the entrance to the stopes or directly inside the stope. Cooling of the air at stope entrances is required when the air flow through the mine is not enough and thus requirements for the recirculation of air are necessitated. This type of cooling is preferred to cooling inside the stope because it is more practical to implement and it is more economical. Furthermore, cooling of the air at the entrance requires less refrigeration capacity than bulk air coolers that are affected by air leakages and temperature.

Spot coolers have a capacity that ranges between 70kW and 350kW. Heat is normally rejected to the mine service water at temperatures of between 35°C and 45°C. Insulated piping helps to prevent the heat from contacting intake airflows. The service water flow rate varies depending on the temperature but, it is about 0.02l/s per kW of cooling at 21°C water temperature.

As mentioned above leakages if not managed can generate humidity in the crosscuts and haulages and potential mud rushes in stopes and orepasses. In-stope cooling also requires further research and manufacturing of more mobile units to operate within a stope.

Air cooler should be kept as close to the face as possible and for convenience should be relocated at the same time that the face scraper winch is moved forward (typically every 40m face advance). Air coolers should be sized and fitted with skids to facilitate manhandling within stopes.

Spot coolers are heavy and difficult to move hence they should be manufactured in such a way that allows for easy instalment and maneuverability. It is also essential for them to be serviced and to undergo maintenance regularly.

5.6.2.1 Previous research and trials have been conducted on cooling cars in the cross cut what recommendations can be suggested to improve their cooling efficiency?

Cooling cars are considered as secondary cooling systems and should be implemented to supplement a mine's existing ventilation and refrigeration system if this is feasible. Some 20 years ago, quite a bit of research was conducted on cooling cars located in the stope cross-cut and in-stope spot coolers; however, not enough trials had been conducted on in-stope spot coolers to provide definitive recommendations. Currently, cooling cars are widely used, and when operating properly can provide sufficient cooling (due to their positional efficiency) to the stope environment. The cooling car system consists of a fan, a cooling coil that should be washed regularly, depending on the dust it is exposed to. Additionally, the research indicates that the cooling cars must be complemented by efficient central ventilation and reticulation systems in order to achieve the design nominal duty.

5.6.2.2 Recommendations for Cooling Cars and Spot Coolers

The following are some of the recommendations for in-stope cooling based on the Deepmine Project (Butterworth, et al., 2001):

- Water usage should be between 0.8t/t and 1.5t/t;
- The wet bulb temperature of stope intake air should be about 28°C to reduce in-stope cooling requirements;
- Pre-cooling of stope intake air should be conducted close to the stope entrances;
- Water usage in stopes should be controlled; leaks and the discharge of chilled water onto rock surfaces should be avoided;
- In-stope air coolers should be in operation an hour before a shift starts until the end of the shift;
- In-stope coolers should have a nominal duty of 60kW;
- An air velocity of 1m/s should be on the stope face for adequate air cooling power;

- In operations that use backfill, it should be cooled to 25°C or less so that it does not add to the heat load at the stope; and
- Chilled water to air coolers should be provided 1 hour prior to the start of the working shift.

The efficiency of a spot cooler can be improved by designing it with a closed loop water cycle to avoid the evaporation of water and increase which leads to humidity downstream from the stope.

Recommendations for research and development to design and develop an in-stope cooler that is light, portable, affordable, and compatible with the cooling necessities of a mine. Moving the in-stope cooler from one panel to the next ought not to hinder the production schedules. Spot coolers can be effective if the correct engineering practices are followed, additionally, consistent maintenance services from the manufactures should be considered and not be given to the workers as their responsibility to achieve the best efficiency output of these cooling systems i.e. the service providers should be contracted outside of the mine.

The human challenge was raised by the interviewees highlighting that the workers were mostly concerned about bonuses and meeting the target. With the increasing issues of health being raised, workers must be trained and educated so that they can understand the risks. Other factors also need attention like focusing the chilled air to the work face as that is where the workers would need it most. Currently, ventilation controls are poor. Backfill can be used as one method to improve ventilation controls and diminish the impact of heat being sourced from the exposed rock faces.

It is recommended that chilled water be supplied to the stope as cold as is practically possible, with 12°C, being recommended in order to minimise in-stope air cooler requirements. The added benefit of the colder supply of water is that it promotes more compact in-stope air coolers and reduced air cooler water usage.

In most cases, air temperatures measured in stope returns exceeded 27,5°C by a considerable margin, despite the liberal use of chilled mine water in the panels and with excessive leakage in back areas. During periods of peak consumption, e.g. during drilling and water jetting, the temperature of the air leaving panels was observed to be higher than 29,5°C. These observations support the argument that unrestricted use of chilled water discharging freely onto rock surfaces is an ineffective way to cool air.

It is recommended that national research programmes, such as SAMERDI should investigate the manufacture of in-stope spot coolers to meet the need of the industry. Further, manufacturers of cooling cars should look to modify the cooling cars to be less demanding of maintenance and move towards real-time monitoring of all cooling cars.

To avoid hot stope conditions at the start of working shifts, it is necessary to operate cooling car air coolers continuously. In–stope air coolers should ideally be operated from 1-hour before workers enter the stope at the start of the shift up to the end of the shift. Again, the use of 4IR technology should be used to facilitate the remote management of all cooling systems.

5.6.2.3 Cooler Water and Air Requirements

In a stope, the air-water ratio is also limited by available face air quantity. The use of higher airflow rates will result in the recirculation of cold air and will severely reduce air cooler performance. The minimum face air quantity is 4.5m^3/s (3m x 1.5m x 1m/s). However, in practice this air quantity could vary between panels and for different stopes and a safety margin of 20% should be introduced when considering air cooler design. Therefore, an airflow rate of 3.6m^3/s (4.5m^3/s x 0.8) is proposed for air coolers. This yields an air-water ratio of 4.3 (6.4 kg/s/1.5l/s) at 5000m depth and 3.5 at 3000m. The air-water ratio increases with depth due to air density dependence. These air-water ratios are considered appropriate.

5.6.3 What is the potential use of cooling rooms, rest periods, work cycles, and recommendations for drinking water in a hot working environment?

The use of cooling rooms has not been well researched, nor reported. For Mine A, they consider cooling rooms to be a challenge to productivity, as management views it as an alternative for workers to hide and stay for longer periods in those cooler rooms. Rest periods have also been viewed negatively because they would require "…discipline and maturity…" from the workers in order for rest periods and rest rooms to be implemented. The two concerns would require further research as very little literature has been found regarding rest periods and cooling rooms. The researcher finds the attitude of the mine to be very Draconian, and this attitude needs to be adequately addressed to promote a zero harm environment, noting the Canadians use environmental temperatures to guide the work duration between breaks.

The South African mining industry has not conducted sufficient research in the use of cooling rooms, hence it is recommendable for further research to be carried out on the subject.

This, along with the poor hydration status of workers at the start of and during the shift indicates that education at all levels (workers, supervisors, management) about the need to report to work well-hydrated, and then to drink sufficient fluids during the shift (including the provision of palatable, potable water on the job), would substantially reduce heat illness in mine workers. Providing readily accessible cool drinking water (12°C–15°C) and encouraging all employees to drink a cup of water every 15 minutes to 20 minutes is recommended to prevent heat stress. Hydration is not the only risk factor in developing heat illness; nor should the management of hydration be used in place of maintaining adequate environmental conditions in the workplace or reducing the physical work rate where practical. It is, therefore, necessary to investigate the effect of shift work and sleep-related fatigue on sleep patterns and, subsequently, on health and safety.

5.6.4 What is the current maximum temperature in light of a zero-harm environment and future requirement of the Mining Charter introducing near equality in the employment of women?

A shortfall to the South African heat stress management system is that it is based on temperature limits that were established many years before there were any female workers in the stopes thus, in the opinion of some of the interviewers, current regulations do not take into account the heat tolerance levels for women. It is highly recommendable that research further investigates these heat stress management standards and governmental regulations.

Another concern that remains to be addressed relates to differences between men and women workers in mining. In reality, women are not the same and their differences come into play when one looks into their challenges and coping strategies. The area where one comes from (rural or urban), one's age (young or old), and health and physical conditions all play a role in what one considers a challenge and what one does not. Further research is required to fully understand how environmental conditions impact the 21st century worker, as well as specifically women working in hot underground environments.

The dissertation is of the opinion that the current legal standards should be reviewed as the current limit of 32.5°C (wb) no longer reflects current safety requirements and is out of sync with other international standards; noting that South Africa gold and platinum mines, unlike other international countries, conduct a labour intensive mining method in narrow vein conditions. In any workplace in an underground mine, and any tunnel under a surge stockpile on the surface of a mine, the manager of the mine must safeguard that: if the wet bulb temperature surpasses 25°C (wb), an air velocity of not less than 0,5m/s is provided (New South Wales Government, 2014).

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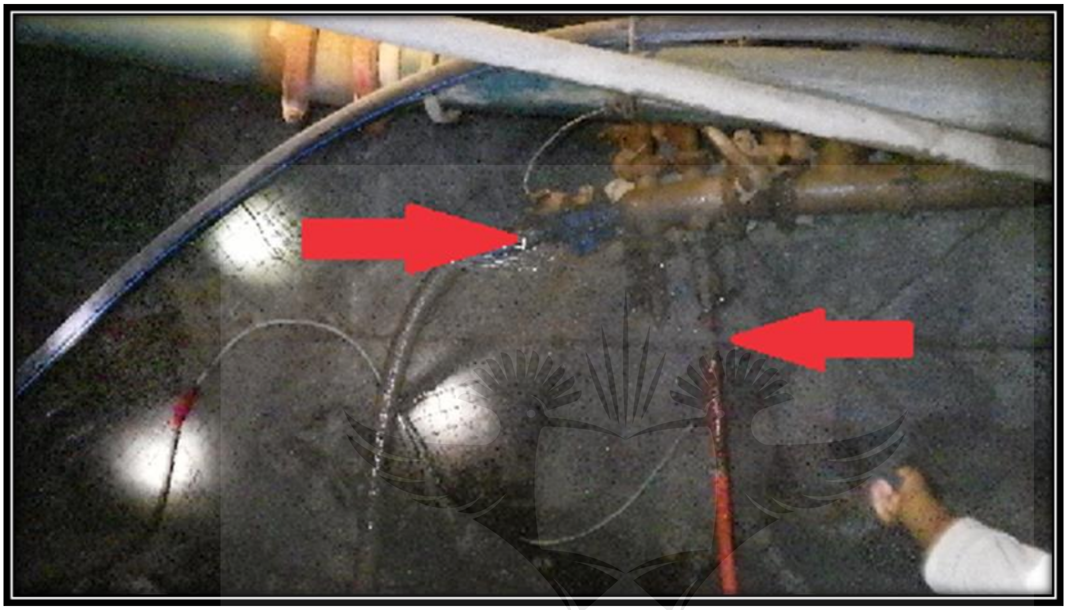
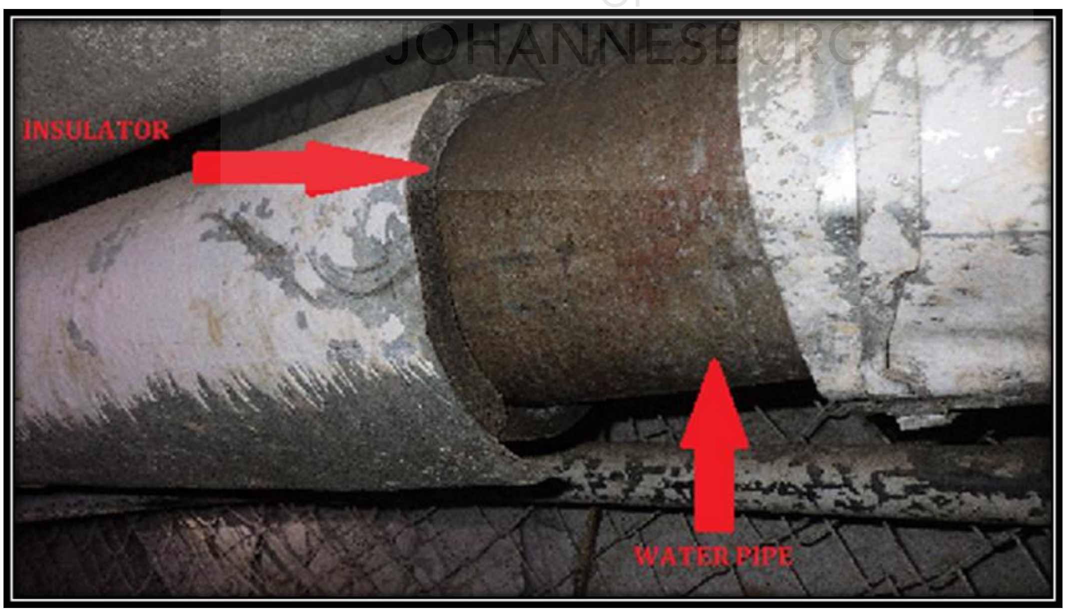
APPENDICES

APPENDIX 1: Showing Leakages (courtesy of Mine C, 21/06/2019)

This section contains additional information related to the research, but not considered essential to the main findings. Below are images captured during an Underground Mine visit at Mine A



APPENDIX 2: Image of an insulated water pipe (courtesy of Mine A, 21/05/2019)



APPENDIX 3: Image showing a ventilation pipe, fan, chilled water pipes, and ventilation door (courtesy of Mine B 21/07/2019)

APPENDIX 4: The photo was taken underground of a cooling car (courtesy of Mine D, 18/03/2019)

APPENDIX 5: Employees affected by Heat Stress at Mine A from 22/01/2019 to 20/03/2019

Images of the tables with the details of the employees that were affected by Heat Stress at the Case Study (Mine A)

Company Nuber	Age	Job	Workplace	Date of Incident	Date of Diagnosis	Temp Wet Bulb	Temp Dry Bulb	Velocity	Final DIAG
A5964038	36	Rock driller	Level 69 Haulage South	2019-01-04	2019-01-22	29.5	32.5	0.35m/s	Heat Cramps
B5370439	40	Rock driller	Level 71 -35 X/Cut	2019-01-04	2019-01-22	29.0	32.0	0.32m/s	Body Cramps
C1839255	36	Rock driller	75 53 S9	2019-01-08	2019-01-22	28.4	30.6	0.8m/s	Heat Cramps
C5980647	37	Scraper Winch Operator	71 47 N8	2019-02-11	2019-02-13	30.4	31.4	0.95m/s	Body Cramps
D0650469	54	Loader Operator	75-73 S1	28.02.2019	2019-05-03	31.0	32.0	0.4	Heat Cramps
E5974219	29	Machine operator	73-64 N10	28.02.2019	2019-05-03	31.5	35.0	0.3	Body Cramps
F0963436	56	Scraper Winch Operator		05.03.2019	08/03/2019	30	33,4	0,5	Body Cramps
G1893977	41	Machine operator	75 Haulage South	06.03.2019	22/03/2019	29.0	34.5	0.8	Body Cramps
H5998737	29	Scraper Winch Operator	69-75 N18	06.03.2019		30.5	32.0	0.7	Heat Cramps
I9126278	28	Stope Team Member	69 74 S3	15/03/2019	25/03/2019	29.5	30.8	0.4m/s	Body Cramps
J1459548	52	Machine operator	73-38 S3	18/03/2019	20/03/2019	31.5	34.0	0.52m/s	Body Cramps

APPENDIX 6: Showing details of Heat stress at Mine A victims from 27/03/2019 to 03/05/2019

Company Nuber	Age	Job	Workplace	Date of Incident	Date of Diagnosis	Temp Wetbulp	Wet Bulp	Velocity	Final DIAG
K7570312	38	Scraper winch operator	73 -38 S3 Panel	2019-03-26	27/03/2019	31.0	34.2	0.52m/s	Body cramps
L5607653	27	Development Team Member	75 41 S9	2019-04-06	12/04/2019	32.0	34.5	1.0m/s	Body Cramps
M0743849	36	Rock driller	73 64 N6	2019-04-09	12/04/2019	31.0	32.0	0.55m/s	Heat Cramps
N3163956	24	Stope team member	69 74 N6 Panel	2019-04-23	23/04/2019	31.5	33.0	0.45m/s	Heat Cramps
Z9107325	35	Stope team member	71 37 N2	2019-04-24	30/04/2019	30.5	31.0	0.6m/s	Body Cramps
O6758187	28	Stope Team Leader	71 40 S/Over	2019-04-24	30/04/2019	30.0	31.0	3.0m/s	Body Cramps
P3160971	36	Rock driller	71 - 38 S3	2019-04-24	30/04/2019	31.6	34.5	1.1m/s	Heat Cramps
Q2503552	42	Rock driller	75 40 S1	2019-04-24	30/04/2019	31.2	34.5	0.6m/s	Heat Exhaustion
R6210981	26	Scraper Winch Operator	75 41 S7 Panel	2019-04-26		32.0	35.0	0.4m/s	Heat Cramps
S1853943	58	Rock driller	71 -38 N2/N4	2019-04-30	03/05/2019	31.8	34.5	1.1m/s	Body Cramps
T5980400	35	Scraper Winch Operator	75 38 N2	2019-04-30	03/05/2019	31.3	34.5	0.53m/s	Heat Cramps

APPENDIX 7: Questionnaire for the Interviews and Discussions

Dear participant:

My name is Tendai Mapeta, I am an Mtech student at the University of Johannesburg. To complete my dissertation, I am conducting a study with the following title: “A study of Ventilation and Cooling in gold mines in South Africa to improve safety and productivity”. This research aims to study the current temperatures being experienced underground, and the ventilation and cooling systems being adopted.

The targeted respondents for the questionnaire are ventilation specialists since they are well informed and have the experience and opinions acquired over time.

The discussion will only require approximately 15 minutes to complete. Participation in this study is voluntary (no one is compelled to participate) hence there will be no incentive or award. To ensure that all information remains anonymous and confidential, please do not include your name. If you choose to participate in this study, please answer all questions as honestly as possible. The information obtained from this study will not harm anyone and will not be used to jeopardise your employment. If in the process of completing the questionnaire you feel uncomfortable to continue, please feel free to stop the discussion.

Thank you for taking the time and effort to participate. The data collected will provide useful information in order to complete my Masters Degree Programme. If you require additional information or have questions regarding the study which I am conducting, please contact me at the numbers listed below.

Sincerely

Tendai Mapeta

084 905 6119

tendai.mapeta@gmail.com

Instructions:

- **Read the questions carefully**

- **Tick ONLY ONE answer to every question unless specified**
- **You may answer with a pen or pencil**

Section A: Personal Questions

The purpose of this section is to have an understanding of the participant as it may have an influence on their opinion.

1. Age

2. Gender

Male	
Female	

3. Designation

4. Company

5. Work Experience

0-1 yr	
2-3 yr	
4-5 yr	
>5 yr	

Section B: Underground Ventilation and Cooling

This section comprises research related questions

6. What are the recommendations you have on applicable stope cooling systems?

a) And what methods are specifically used at the mines?

b) Are there any challenges related to underground cooling that you have observed or are aware of?

c) And how do you think we can overcome these heat related issues?

7. What are the most heat challenging mines or sections of mines that you might be aware of i.e. where do you suggest mine visits?

a) What temperatures are experienced at these mines?

8. What is your opinion of the implementation of rest periods in cooling rooms?

a) Do you know of any mine currently using cooling rooms?

9. What do you think are the benefits of using cooling garments if any?

a) Do you know of any mine using cooling garments?

b) In your opinion is their application generally effective?

c) If so, what are the available cooling garments, and do they serve their purpose?

d) What mechanisms of cooling are the cooling garments using?

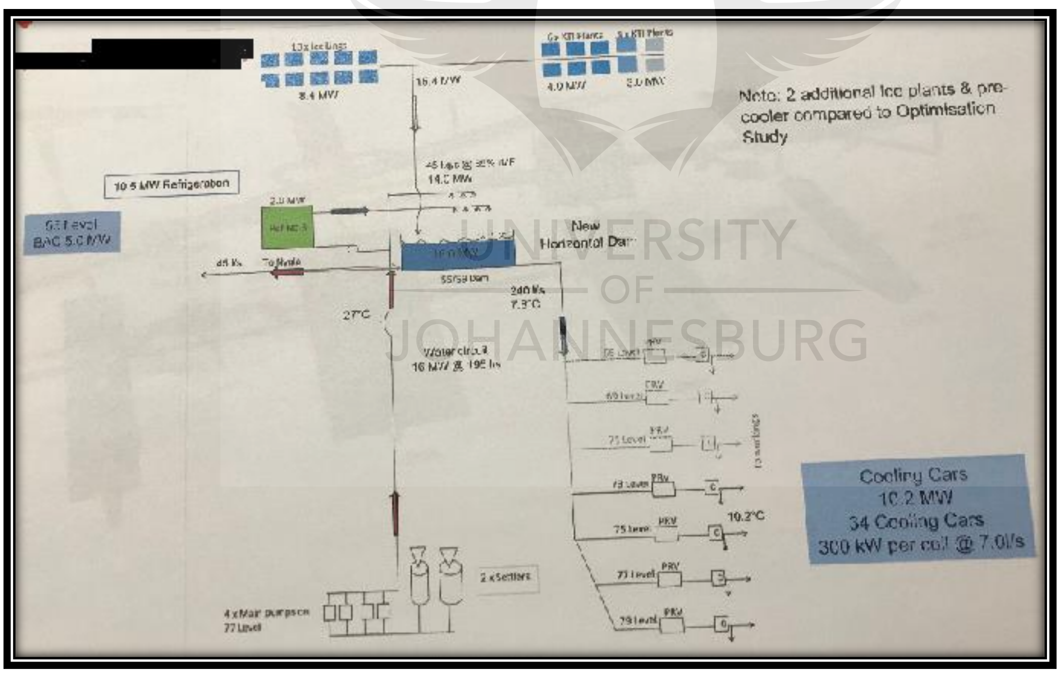
e) Are cooling garments affordable and are they personalised or shared amongst the workers?

10. What are your views on the safety of women working instope temperatures above 27.5°C?

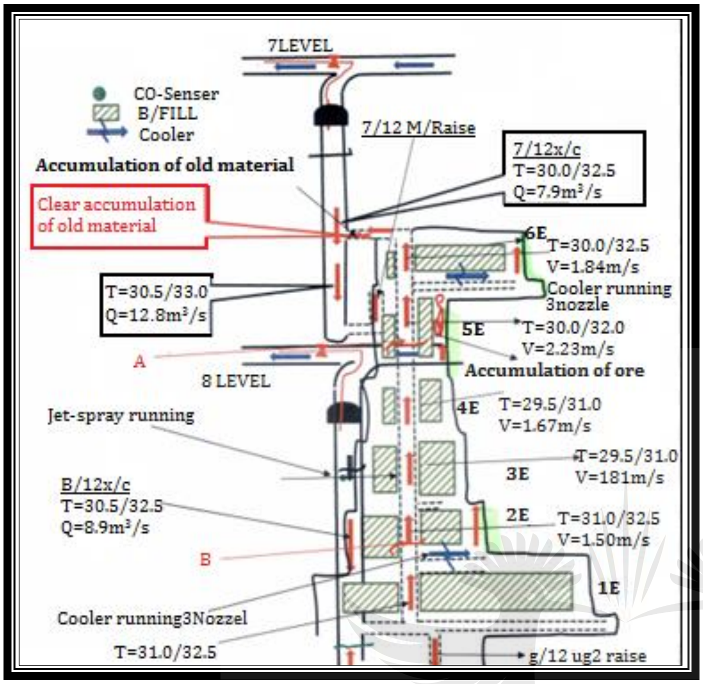
11. What are your thoughts on 27.5^{0}C (wb) for heat tolerance and 32.5^{0}C (wb)for maximum?

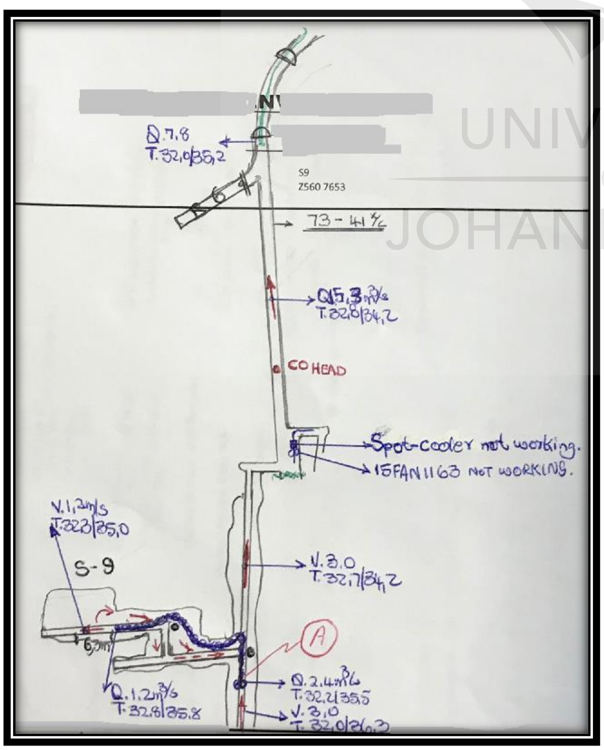
a) Are these temperature limits still correct in current concerns with safety unionism etc. or should they be reviewed?

APPENDIX 8: Showing Ice System used at Mine A

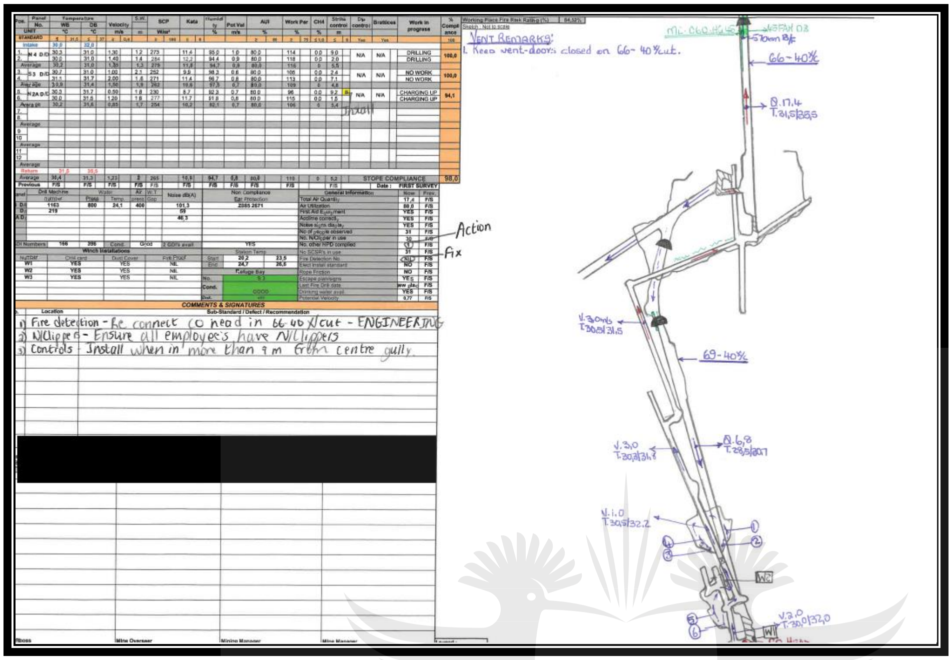


APPENDIX 9: The following images are examples of ventilation reports and temperature records of cooling cars used at Mine B





APPENDIX 10: The following images are examples of ventilation reports and temperature records of cooling cars used at Mine D



Cooling Car Report - March/April 2019

	Position	Date audited	Number	Designed size (kW)	Duty (kW)	Water flow rate(l/S)	Quantity m³/s	C/Car pump installed	Non return valve	Dumping valve	Air Temp Wet	Air Temp Dry	Air Temp Wet	Air Temp Dry	Water Temp In	Water Temp Out
1	66 - South dev(@ 38)	15-Jan-19	K 11	500	134	10.3	11	No	No	No	27.5	29	25	25	19.3	22.4
2	66 South Dev(@36)	New														
3	69 - 75 X/Cut	1-Apr-19	K 14	500	159.4	6	8.5	No	No	No	33	37	29.8	31	19.5	25.8
4	69 - 71 X/Cut	STOPPED														
5	71 - 73 X/Cut	18-Jan-19	N/V	500	288	8.8	9	No	No	No	28	30	21	21	11.3	19.1
6	71 - 74 X/Cut	16-Jan-19	K 24	500	332	11.3	12	No	No	No	30	32	24.5	24.5	15.0	22.0
7	71 - Haulage South	30-Apr-19	K 24	500	178.6	7	11.2	No	NO	NO	31.8	33.5	29	30	20.5	26.6
8	73 - Haulage South	28-Mar-19	PHAS	500	151	5.3	8.8	O.O.O	NO	NO	29.8	34.5	26.5	27.5	20.0	26.8
9	73 - 40 X/Cut	24-Apr-19	K 23	500	131.4	3.6	9.2	Yes			29.7	30	27	27	18.2	26.0
10	73 - 38 X/Cut	9-Apr-19	K 17	500	112.3	6	7.3	No	No	No	29	31	26	27.5	21.5	26.0
11	73 - 37 X/Cut															
12	75 - 77 X/Cut	4-Apr-19	K 08	500	145.6	6.6	8.5	N/A	N/A	N/A	32	35	29	30.6	20.5	25.8
13	75 - 44 X/Cut	15/03/2019	H 01	500	184.3	5.1	11.4	No	No	No	30	32.7	27	27	20.3	29

Mar-19 — **Developing**

Name of Working Place	Date of Survey	Ref number	Del m³/s	Through vent Q	Intake TWB	Intake TDB	Face Vol m³/s/m²	Face Kata	Leak %/100m	Column Face	Face TWB	Face TDB	Number employees	N/Clippers use	W/Place rating %	Station temps WB°C	Station temps DB°C	Number of winches	Winches covered	Vel m/s	Int Q	Contr to F	Dip Contr inst	Strike Contr inst	Cool car	C/G brat	Work Per %	AUI %	TW
66 Alimak	29-Mar-19	X	5.5	21.6	26.5	29	0.75	12	10	12	28.5	33	4	4	85	20.2	25.6												
69 - 74A T/Way																													
69 - 74 A Raise																													
69 - 75 T/Way	4/2/2019	59	4.3	9.8	30	31.5	0.49	7.7	36.6	11.7	31	34.5	6	6	81	22.2	26												
73 - 75 T/Way	23-Apr-19	Heat Inv	3.0	5.2	30.0	31.5	0.40	8.0	10.2	12.0	31.9	34.5	2.0	2.0	75.0														
75 - 75 T/Way	04/Apr/19	60	1.2	13.9	27.0	33.0	0.26	7.2	19.1	12.0	31.0	34.0	4.0	4.0	56.0	22.2	26.0												
75 - 74 B X/Cut	04/Apr/19	61	2.2	13.9	30.5	33.0	0.20	5.6	49.7	12.0	31.6	36.8	7.0	7.0	55.0	22.2	26.0												
66 - Haulage South	16/Apr/19	62	3.8	14.2	24.0	28.0	0.35	9.7	8.2	12.3	29.0	31.5	8.0	8.0	85.0	20.8	24.5												
66 - RAW South	16/Apr/19	63	3.9	14.2	24.0	28.0	0.36	11.7	10.7	10.1	27.5	30.0	9.0	8.0	85.0	20.8	24.5												
66 - 35 X/Cut	16/Apr/19	64	2.3	14.2	24.0	28.0	0.21	8.1	41.6	11.5	29.5	34.0	6.0	4.0	78.0	20.8	24.5												
66 - 36 Raise	16/Apr/19	65	2.4	15.3	29.0	32.0	0.50	9.1	37.5	16.0	30.0	32.5	4.0	4.0	85.0	20.8	24.5												

APPENDIX 11: Liquid cooling garments with tubings embedded inside (Sarkar & Kothari, 2014) and Optimal design of Vortex Tubes of Mine Cooling Jacket